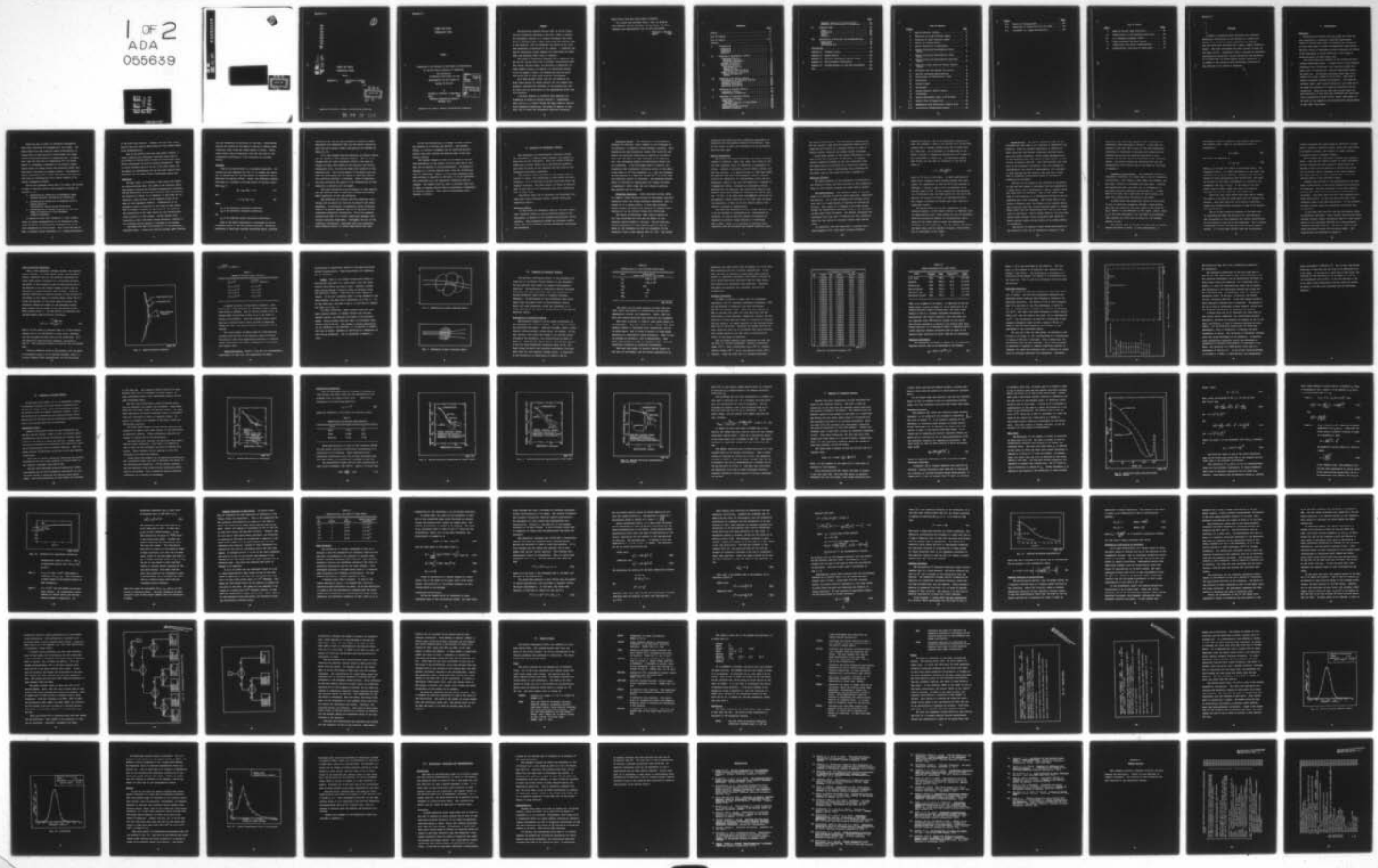
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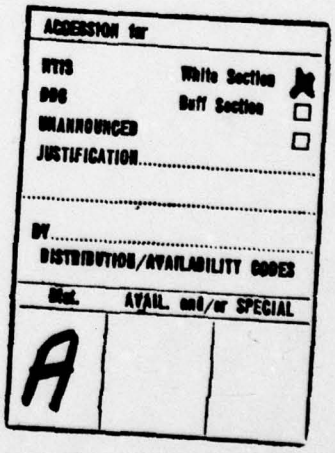
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LASER TEST RANGE PROPAGATION MODEL

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science



by

William H. MacInnis, B.Eng.Phys.
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December 1977

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Preface

The Electronic Warfare Division (WR) of the Air Force Avionics Laboratory expressed a need for a model to predict the atmospheric effects on a slightly divergent laser beam which is reflected from a small corner-cube and received back at the receiver. Such an experiment was being set up, with beam parameters as described in this report. I undertook the task of developing a model adequate for describing the experiment and hopefully other cases of interest.

The study of atmospheric phenomena was a completely new one for me, and you will find no original contributions here. This study, and this model, are basically a compilation of other peoples results, as applied to a particular problem. A list of people to whom I am indebted for help and guidance would have to start with my entire bibliography.

On a more personal level, however, my thanks go to: Major Bruce Pierce, my thesis advisor, for his support and guidance, and Major Ron Grotbeck, of the Avionics Lab, for his help with the description of the experimental system and with finances.

I am also indebted to Professor Donn Shankland for attempting to guide me through Tatarski's labyrinthean work, and to S. A. (Tony) Clough, and many others at the Air Force Geophysics Laboratory, for trying to show me, in one week, how to handle the atmospheric molecular absorption

models which they have taken years to develop.

On a still more personal level, I want to thank my wife, Marilyn, and our children, Kim and Scott, for their tolerance and understanding over the past few months.

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Contents

		Page
Preface		ii
List of Figures		vi
List of Tables		viii
Abstract		ix
I.	Introduction	1
	Background	1
	Objectives	3
	Approach	4
II.	Overview of Atmospheric Effects	7
	Molecular Effects	7
	Molecular Scatter	8
	Molecular Absorption	8
	Aerosol Attenuation	9
	Refractive Effects	10
	Non-random Effects	10
	Random Effects	12
	Irradiance Scintillations	13
	Angle of Arrival Variations	16
	Phase Fluctuations	18
	Wander	19
III.	Modeling of Molecular Effects	21
	Distribution of Molecular Species	21
	Standard Atmospheres	23
	Molecular Scattering	25
	Molecular Absorption	26
IV.	Modeling of Aerosol Effects	30
	Atmospheric Models	30
	Simplifying Assumptions	33
V.	Modeling of Turbulent Effects	38
	Turbulence Strength	39
	Beam Wander	40
	Temporal Behavior of Beam Wander	46
	Mean Irradiance	47
	Irradiance Scintillations	48
	Aperture Averaging	53

Page

Temporal Behavior of Scintillations 54
Probability Distribution of Irradiance . . . 55

VI. Combined Model 63

Input 63
Subroutines 65
Output 67
Results 73

VII. Conclusions, Discussion and Recommendations . . 76

Conclusions 76
Discussion 76
Recommendations 77

Bibliography 79

Appendix A: Program Listing 83

Appendix B: Sample Results 120

Appendix C: Molecular Absorption Computer Codes . . . 139

Appendix D: The Log-Normal Distribution 151

Appendix E: Program Changes to Vary Beam Parameters . 155

Vita 156

List of Figures

Figure		Page
1	Angle-of-Arrival Geometry	17
2	Deflection by Large Turbulent Eddies	20
3	Spreading by Small Turbulent Eddies	20
4	Results of Program HIRACC	27
5	Aerosol Extinction in Wavelength	32
6	Aerosol Extinction Approximation (Rural Model)	34
7	Aerosol Extinction Approximation (Urban Model)	35
8	Aerosol Extinction Approximation (Maritime Model)	36
9	Refractive Index Structure Factor, Typical Values	41
10	Parameters for Beam Wander Calculation	44
11	Aperture Averaging Approximations	54
12	Relationship of Characteristic Times	59
12	(continued)	60
13	Printed Output	68
13	(continued)	69
14	Plotted Results, Default Values	71
14	(continued)	72
15	Typical Experimental Data (1.06 microns)	74
C-1	Overall Flow of Program LIN	142
C-2	Homogeneous Path Calculation (Program LIN)	143
C-3	Line-by-Line Transmittance Results	145

Figure		Page
C-4	Results of Program LASER	146
C-5	Comparison of Output From LIN and HIRACC	148
D-1	Log-Normal vs. Normal Distribution	152

List of Tables

Table		Page
I	Range of Arrival Angle Variations	18
II	Mixing Ratios of the Uniformly Mixed Gases . .	22
III	U.S. Standard Atmosphere (1962)	24
IV	Model Atmosphere Sea Level Values	25
V	Coefficients for Aerosol Approximations	33
VI	Characteristic Time Scale of Beam Wander . . .	47

Abstract

A model is described which calculates the irradiance probability distribution at the receiver of a system consisting of a co-located laser transmitter and receiver, with the beam being reflected from a small, highly reflective target. The beams considered have short pulses (10 nsec) at low rates (30 Hz). Atmospheric effects included are molecular scattering and absorption, aerosol extinction and turbulence. It is found that, in normal daytime weather conditions, it is common to have pulse-to-pulse irradiance variations at the receiver of two orders of magnitude.

I. Introduction

Background

The Electronic Warfare Division of the Air Force Avionics Laboratory is currently conducting experimental studies of pulsed laser beams to determine the feasibility of using such beams in future countermeasures applications. The basic series of experiments entails measuring the effects of the atmosphere on pulsed beams over a test range at Wright-Patterson Air Force Base, Ohio.

The laser being used operates in the visible and near-infrared wavelength region. It emits beams at the Neodymium wavelength near 1.06 microns, the frequency doubled wavelength near .53 microns, and a variable wavelength between the other two. The variable wavelength beam comes from a tuneable dye laser, pumped by the Nd beam. Each beam is slightly divergent (several milliradians). The beams are reflected from a small corner reflector at the other end of the range and detected by a receiver collocated with the transmitter. These are low duty-cycle pulsed beams with pulse durations of less than ten nanoseconds and pulse repetition frequencies of about 30 Hz. Hence, peak powers on the order of ten megawatts are developed with average powers of only about three watts.

There has been no model of atmospheric propagation which fully describes the propagation of such beams. Most recent effort has been directed toward investigating continuous wave or high duty-cycle pulsed lasers for energy transfer (including weapons) or communications. In particular, work has been done on compensating for the random effects of atmospheric turbulence in the optical communications field and energy losses and defocusing effects have been widely considered for energy transfer. The AGARD Conference proceedings (Ref 1) from 1976 describe the then current state of investigations into various aspects of the optical propagation problem.

The various phenomena which have to be taken into account in order to describe optical beam propagation through the atmosphere are:

1. scattering and absorption by atmospheric gases (called molecular scattering and absorption)
2. scattering and absorption by suspended solid or liquid particles (collectively called aerosol extinction)
3. scattering due to random variations in the local index of refraction of the atmosphere (called turbulence).

It should be noted that turbulence, in this context, refers to random inhomogeneities in the refractive index, caused primarily by corresponding inhomogeneities in the local temperature of the air mass. This is not the same as what is normally called turbulence; i.e., random fluctuations

in the local wind velocity. Indeed, such wind flow irregularities may well provide good mixing and thus reduce temperature inhomogeneities.

Each of the factors above has been widely studied. A recent international conference, mentioned above (Ref 1), was devoted to sharing recent results and discussing needed efforts throughout the field of optical propagation. There is active research going on in all of the above areas, but the degree of understanding and the data base against which hypotheses can be checked varies considerably among them.

Objectives

The goal then, is to develop a model which will predict on a pulse-to-pulse basis, the power at the receiver, based upon normally reported and forecast meteorological variables. For any application relying upon reflected power measurements for tracking or aiming, it is important to know what sort of variation, pulse-to-pulse, can be expected solely on the basis of the atmospheric effects. Determination of the acceptable level of variation is not a part of this effort. That is clearly a function of the nature of the reflector, the installation of the laser device and the tracking algorithm involved in a real system. For the present fixed installation with a stationary corner reflector, tracking is not a problem and the aiming is considered to be optimum.

The model must take into account all of the mechanisms described above. It must give both the average power received

and the probability distribution of the power. Experimental results are plotted as the number of pulses in various power intervals, after counting a large number of pulses. Hence, these results should essentially have the same form as the probability distribution, if the intervals are suitably chosen.

Approach

Each of the above factors is considered separately. Following the usual approach (Ref 23), it is assumed that Beer's Law is appropriate for the description of attenuation due to molecular and aerosol effects. Hence, the irradiance reaching the plane at a distance x from the source (of initial irradiance E_{eo}) is

$$E_e = E_{eo} \exp(- \sigma x) \qquad (1)$$

and

$$\sigma = \sigma_m + k_m + \sigma_a \qquad (2)$$

where

σ_m is the molecular scattering coefficient

k_m is the molecular absorption coefficient

and

σ_a is the combined aerosol extinction coefficient.

Each of the three coefficients is calculated by use of information which is the most current available. Molecular scattering is based upon Rayleigh scattering theory, molecular

absorption upon the Air Force Geophysics Laboratory (AFGL) Absorption Line Compilation (Ref 21) and aerosol extinction upon the latest aerosol models incorporated into LOWTRAN 3B (Refs 30, 31).

It is then assumed that the molecular and aerosol effects are not coupled to the turbulence effects. That is, it is assumed that the total atmospheric effect is the same as though the power were reduced by the molecular and aerosol attenuation first, and then the beams were subjected to the turbulent path. The various effects of turbulence upon the beam are investigated and the degree to which each affects this particular problem is discussed. Those of importance are then calculated and applied to the determination of what radiation is incident upon the target.

The target reflectivity and divergence are then applied and the reflected beam is essentially treated with another whole application of the same procedure.

The procedures and formulas used for turbulence calculations are not nearly as clear cut as those for the other phenomena. In particular, in moderately strong turbulence, there is no general agreement even as to the nature of the irradiance probability distribution. One of the proposed distributions (Ref 9) is chosen, based upon agreement with closely controlled experiments. Throughout the rest of the turbulence calculations, approaches which have apparently given adequate results in similar applications are used.

In all the calculations, no attempt is made to derive the formulas or to develop new theories. The approach, rather, is strictly a pragmatic one of selecting suitable results from other sources and applying them to this particular problem.

The computer program is meant to be simple to use and self-explanatory in the output, to give a good idea of just what can be expected in system performance. The program is designed on a strictly modular basis, with all calculations done in subroutines. Hence, if it is later determined that more accuracy is required in some area, or if new approaches are discovered, only the appropriate subroutines need be changed. For example (Ref 24), work is currently under way at AFGL on improved aerosol models incorporating a dependence on relative humidity. This could be incorporated with a minimum of trouble.

II. Overview of Atmospheric Effects

The propagation of electromagnetic radiation through the atmosphere is a highly complex subject, some aspects of which are not well understood. There are several different mechanisms involved, which vary in significance depending upon both the nature of the radiation and the nature of the propagation path being considered.

The radiation being considered in the present case is optical in nature, with wavelengths in the visible and near-infrared. It is in the form of pulsed laser beams which are slightly diverging. The beams consist of pulses of duration (PD) on the order of 1-10 nanoseconds and with a repetition rate of about 30 Hz.

The effects which are of importance can be grouped into three main areas: molecular effects, aerosol effects, and refractive effects.

Molecular Effects

In the context of atmospheric physics, the term "molecular" generally refers to the gas molecules making up the atmosphere, as opposed to any suspended particulates, called aerosols. Beams propagating through the atmosphere suffer losses due to two different molecular mechanisms--scattering and absorption.

Molecular Scatter. The scattering of electromagnetic radiation by particles, small compared to the wavelength of the radiation, is generally called Rayleigh scattering. Such scattering has been extensively studied (Ref 4:651-652) and results are available concerning all aspects of the effect. Since only the amount of light scattered is of importance here, the interesting angular and polarization effects are not considered. In the wavelength range of interest, the attenuation due to molecular scattering losses is very small, on the order of 10^{-3} per kilometer; i.e., over one kilometer, the transmission of a beam will be $\exp(-10^{-3})$ or 99.9%, when only molecular scatter is considered. The molecular scatter effect is included for completeness even though the effect is negligible, except under the very clearest conditions when aerosols are not a factor.

Molecular Absorption. Unlike molecular scatter, which is a smooth, slowly varying function of wavelength, molecular absorption shows very strong wavelength dependence. This is because it is a quantum effect, in which each molecular species present can absorb only radiation of energies corresponding to its own internal energy level differences.

The amount of absorption, then, clearly depends not only upon wavelength but also upon the amount of each absorbing species present in the path. The Air Force Geophysical Laboratory has been compiling data on both the makeup of the atmosphere and the line parameters for the absorption lines of each species (Refs 21, 22). This latter

compilation has drawn from both laboratory measurements of absorption and from quantum mechanical calculations. Chapter III covers in detail the calculation of the attenuation from this data base.

Aerosol Attenuation

The effects of aerosol attenuation are those with which everyone is familiar. Haze, fog, smoke, and clouds all fall into this category, hence its importance to propagation is obvious. Methods of accounting for the effect, however, are much less obvious. In a paper published in 1908 (Ref 4:634), Mie obtained from basic electromagnetic theory a rigorous solution for diffraction of a monochromatic plane wave by a homogeneous sphere of any size and composition, suspended in a homogeneous medium. Although most atmospheric aerosol particles are not spherical, the calculations based on this solution yield good information concerning the aerosol problem. In fact, it has been shown (Ref 33:19)that extinction by non-spherical aerosol particles is less than that for spherical particles, so that use of Mie's theory yields a conservative estimate of transmittance.

The basic Mie formulation is for a single particle, but it can be extended to consideration of a distribution of particles, so long as they are randomly distributed and separated by distances large compared to a wavelength (Ref 4 :634). Hence, it is possible to calculate quite rigorously both the scattered and absorbed radiation, given

the aerosol distributions. The calculations themselves are far from trivial, since even the relatively simple case of a single particle results in a lengthy solution in terms of infinite series, which are not always rapidly convergent.

A more basic problem in the aerosol calculations is the need to know the distribution of particles. A rigorous solution requires knowledge of the size, refractive index and number density of particles as a function of position. The difficulties found in determining these parameters and the models used in this study are found in Chapter IV.

Refractive Effects

The bulk properties of the atmosphere, as described by the refractive index, also have an effect on the propagation. There are both smoothly varying and random effects present.

Non-random Effects. The refractive index of the atmosphere is a function of density (hence pressure), temperature and humidity. All of these parameters have average values which vary in a smooth manner as functions of altitude and position. This results in a bending of the light passing through any significantly different layers of the atmosphere at other than normal incidence. For example, navigators and astronomers have long used a correction for this refractive effect for the viewing of celestial objects away from the zenith.

In principle, much the same effect is present when a beam propagates over a path which includes different

temperature regions, even at an essentially constant altitude. For example, a beam at low altitude will be bent when crossing over a boundary between woods and a plowed field on a sunny day. As an estimate of the magnitude of this effect, consider a temperature difference of 10^{o} C which is not unreasonable in bright sun. An approximate formula (Ref 34:102) for the index of refraction in the optical region is

$$n = 1 + \frac{80 \times 10^{-6}\, p}{T^{o}} \qquad (3)$$

with T in ^{o}K and p in millibars. A simple application of Snell's Law, assuming a sharp boundary between the areas, yields, for temperatures of 295 and 305 ^{o}K and pressure of 1000 mbar, a change in angle of 8.9 microradians for an incident angle of 45^{o}. If this happens near the beginning of a 10 kilometer path, the beam position at the end of the path will be moved 8.9 cm from its unperturbed position. For a highly collimated or focused beam, this could be a significant factor.

For systems which use two way propagation, as with reflected signals, or with beacon signals, as sometimes used in communications links, these effects are not of importance, since the reciprocity inherent in the geometrical optics nature of the effect leads to equal and compensatory refraction in both directions. For this reason, and because the beams being used are somewhat divergent, these effects are not considered in this model.

Random Effects. The optical refractive index of the atmosphere has been seen to be a function of temperature and pressure. These two physical parameters, in addition to their relatively well-behaved variations described above, also have random components. These random inhomogeneities in the atmosphere have been treated in great detail, in particular by Tatarski (Ref 34). This book describes the structure of the turbulent fluctuations, from both theoretical considerations and results of measurements. His treatment is very thorough and has served as the basis for a great deal of subsequent investigation aimed at verifying or extending the treatment.

The basis of the theory of the structure of turbulence is the idea that energy is introduced into the atmosphere on a large scale, with a characteristic size L_o, usually called the outer scale of turbulence. This is most likely some form of local heating, as in differential heating by the sun, depending upon local topography. This heated body of air, called a turbulent eddy, then breaks up into smaller eddies. This continues until the critical Reynolds number is reached. These eddies then are characterized by a size ℓ_o, the inner scale of turbulence. They no longer break up, but lose their excess energy through viscous dissipation (Ref 34:50-54). These turbulent eddies are the source of the random effects on propagation.

The results of applying a small random perturbation to the refractive index (or the dielectric constant) in the

solution of the usual wave equation lead to variations in irradiance, phase and angle of arrival. A great deal of Tatarski's book (Ref 34) and most of the other theoretical literature on turbulence is concerned with improving this approach and solving the resulting equations, or with assuming and testing various distributions of the turbulent eddies. The various effects are described below and the approximations and formulas used in the model are discussed in Chapter V.

Irradiance Scintillations. The predominant effect of atmospheric turbulence on a light beam is that of irradiance scintillation. This effect is what makes stars twinkle, and has been a problem to astronomers for many years. Tatarski has demonstrated that the effect can be considered as a multiple scattering phenomenon (Ref 34:166-177). A great deal of his book, and a great deal of work by others, has gone into understanding the nature of the effect.

A method based upon geometrical optics was first used to try to understand propagation through a random medium. This was only valid for very short paths, on the order of $k\ell_o^2$, where k is the wavenumber of the signal. Hence, since ℓ_o in the lower atmosphere is on the order of millimeters, this approach was valid only for paths of a few hundred meters, at most.

The approach used by Tatarski was based upon an approximation attributed to Rytov. In this approximation, a

perturbation method is applied to the natural logarithm of the electric field. That is, the electric field E is expressed as

$$E = \exp(\psi) \tag{4}$$

and then ψ is expressed as

$$\psi = \psi_o + \psi_1 \tag{5}$$

where ψ_o is the part of ψ which is the vacuum result. The assumption that ψ_1 is a small perturbation is then made, and solutions for ψ_1 can be obtained. Tatarski calls this the Method of Smooth Perturbations (Ref 34:218-258). The range of validity of this Rytov approximation is limited by the assumption that $|\psi_1| << |\psi_o|$. It was found in the late 1960's, that for paths longer than about one kilometer, measured data did not agree well with predictions.

Since that time, many efforts have been made to extend the theory to the case of longer paths and for stronger turbulence. Fante (Ref 10:11-15, 34-38) gives a relatively simple and straightforward discussion of some of the methods and approximations.

One of the most tenacious problems in the whole area of turbulence has been the saturation of log-irradiance. The fluctuations in the irradiance are usually characterized by the variance in the log of the irradiance. This is mostly a carryover from all the work done with the Rytov approximation. It is found (Ref 17:1524) that the log-intensity

variance increases with path length and turbulence strength until it reaches a saturation value. Above that path length or turbulence strength, the variance no longer increases. It actually tends to decrease slightly.

Many attempts have been made to explain the saturation effect. None has been widely accepted by other researchers. Yura has recently (Ref 40) presented a model based upon Tatarski's model with the addition of diffraction and the loss of lateral spatial coherence as the beam propagates. This model predicts, at least qualitatively, all of the observed effects in the saturation region.

Another open question in the understanding of the irradiance scintillations is the actual probability distribution of irradiance. For weak turbulence, it has been generally accepted (Ref 10:42) that the probability distribution is log-normal. This means that the log of the irradiance has a normal distribution. It has also been noted that strong turbulence leads to the same distribution. In the intermediate area, however, there are significant deviations from log-normality.

It has been shown (Ref 37) that the distribution cannot be everywhere log-normal. Other possible distributions being proposed include a normal distribution (Ref 3), small perturbations on the log-normal (Ref 38) and a three-parameter truncated log-normal (Ref 9). The last of these has been rather arbitrarily chosen for the present model. Both distributions are described in Chapter V.

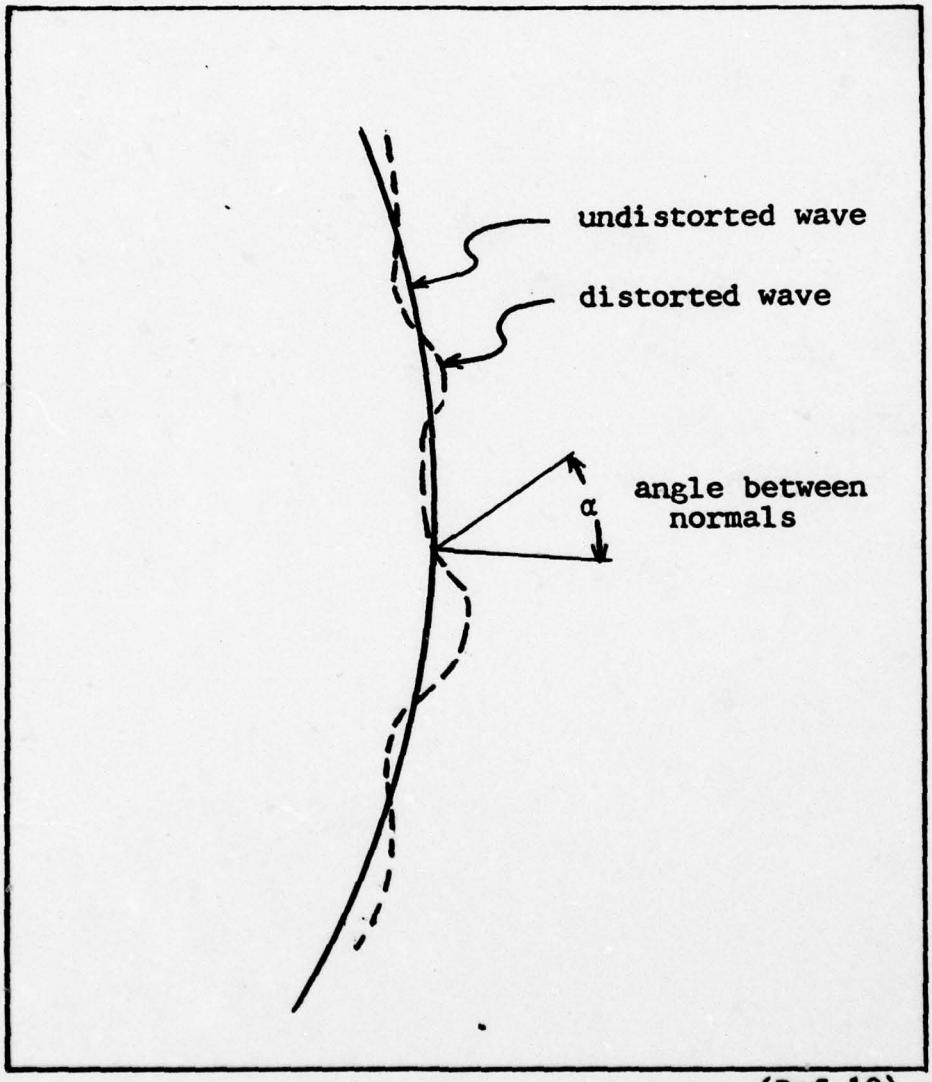
Angle of Arrival Variations

When a wave propagates through a vacuum, the wavefront remains uniform. As a wave passes through the atmosphere, however, different parts of the wavefront experience different phase shifts, resulting in a non-uniform wavefront. The effect of this distortion upon the angle-of-arrival at the receiver (or at the target) depends in part upon the definition of angle-of-arrival (Ref 17:1542). Using the physical description of angle-of-arrival as the direction of the normal to the surface of constant phase, Fante (Ref 10: 44-48) has defined α as the local angle of arrival, the difference between the normal to the perturbed constant phase surface and the normal to the unperturbed (vacuum) phase surface (Fig. 1). He then derives an expression for the mean-square angle-of-arrival flucuation,

$$\langle \alpha^2 \rangle = A \frac{\int_o^x C_N^2(x')dx'}{D'^{\frac{1}{3}}} \qquad (6)$$

where x is the source to receiver range, D' is the receiver diameter and A is a coefficient of order unity, depending upon the strength and scale sizes of the turbulence. C_N^2 is the refractive index structure parameter, discussed on page 39. This expression should be valid for any non-focused beam.

Using an effective value of C_N^2 (constant over the path), a 10 kilometer range, a 10 cm receiver diameter, and A = 3 (to give largest likely fluctuations), we find the values



(Ref 10)

Fig. 1. Angle-of-Arrival Geometry

of $\sqrt{\langle \alpha^2 \rangle}$ in Table I.

Table I

Range of Arrival Angle Variations

C_N^2 ($m^{-\frac{2}{3}}$)	$\sqrt{\langle \alpha^2 \rangle}$ (radians)
5.0×10^{-12}	5.7×10^{-4}
5.0×10^{-13}	1.8×10^{-4}
5.0×10^{-14}	5.7×10^{-5}
5.0×10^{-15}	1.8×10^{-5}

It should be noted, as discussed in Chapter V, that these values of C_N^2 correspond to turbulence levels ranging from strong to extreme. Even in the most extreme case, the average (RMS) fluctuation is seen to be of the order of tenths of milliradians. Since the equipment being considered has a field-of-view at least an order of magnitude larger than this, the angle-of-arrival fluctuation will be ignored.

For a more highly collimated beam and correspondingly narrower field-of-view of the receiver, angle of arrival fluctuations could cause significant variations in received power, particularly for certain combinations of wavelength and receiver size.

Phase Fluctuations. Except in the case of interferometric measurements of some sort, the significance of phase

fluctuations is essentially limited to the angle-of-arrival effect described above. Phase fluctuations will therefore not be considered.

Wander. There is yet another random effect which is particularly pertinent to a narrow beam, unlike the other effects which affect any sort of wave. Consider a narrow beam passing through a series of cells of different sizes and refractive indices. These will act like a series of lenses. If the cell (turbulent eddy) is large compared to the beam diameter, the beam will be deflected, as in Fig. 2. If, on the other hand, the eddy is small, it will tend to broaden the beam, as in Fig. 3.

In strong turbulence, perhaps because there are just more turbulent eddies, or perhaps because they are more sharply defined, the beam may even break up into multiple beams. Various studies have been done to investigate these effects (Ref 10:18-24). Even though a rigorous description of the mechanism is not available, it is possible to predict the sort of wander, spreading or splitting by a comparison of the various parameters. This is described in Chapter V, also.

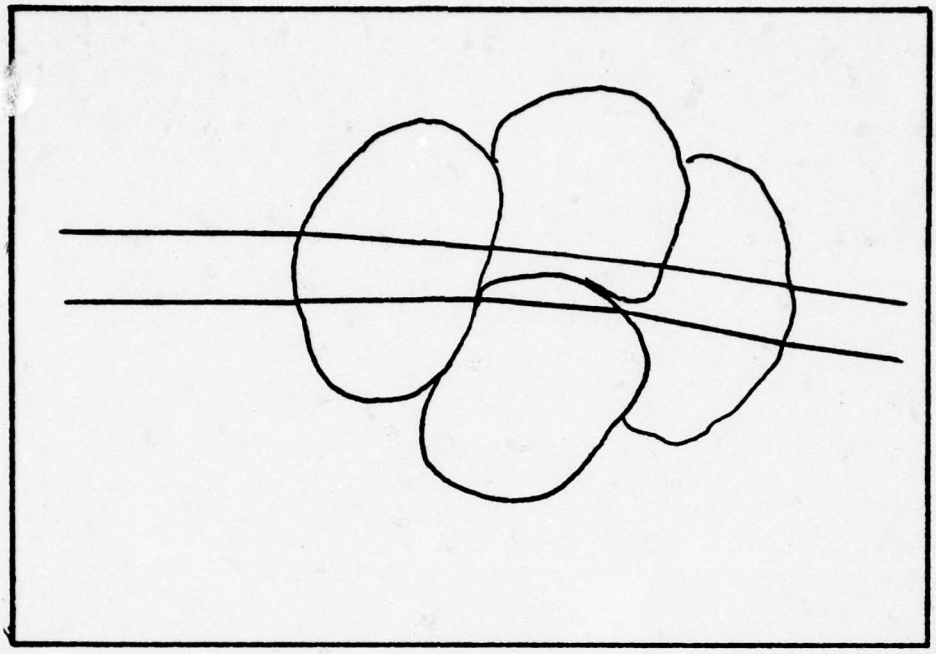


Fig. 2. Deflection by Large Turbulent Eddies

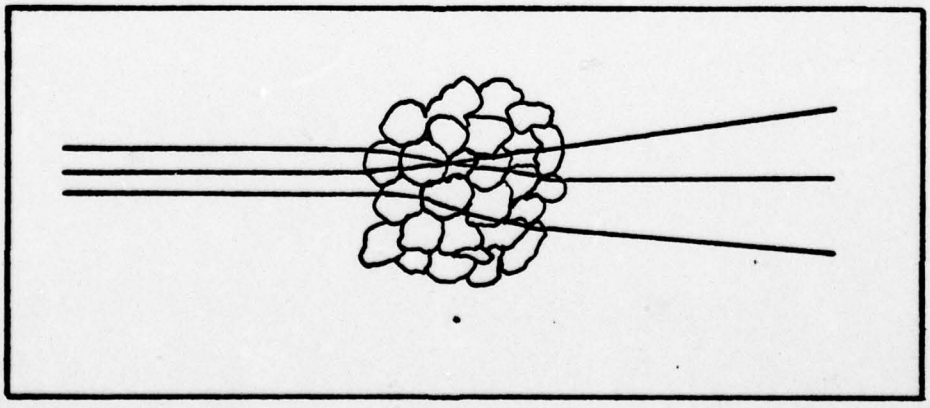


Fig. 3. Spreading by Small Turbulent Eddies

III. Modeling of Molecular Effects

The molecular attenuation effects in the atmosphere are those due to the gaseous species present in the atmosphere. The gas molecules both absorb and scatter electromagnetic radiation. The scattering is essentially classical Rayleigh scattering from small particles, while the absorption is a quantum mechanical effect which is strongly wavelength dependent. The wavelengths at which absorption takes place depend upon the energy levels of each molecular species. Hence, the total absorption, unlike the scattering, is a strong function of the relative concentrations of the various molecular species.

Distribution of Molecular Species

The molecules assumed to be the normal constituents of the atmosphere fall into two classes. One of these is called the uniformly mixed gases. These are nitrogen, oxygen, carbon dioxide, carbon monoxide, nitrous oxide, and methane. As the name implies, these gases are assumed to be uniformly mixed throughout the atmosphere, with concentrations as shown in Table II. These are the values used in the published reports of the Air Force Geophysical Laboratory (Refs 19, 20, 22). These values are based upon extensive measurements over many years (Ref 22), and represent average values. A discussion of the variability of these ratios is found in Ref 23.

Table II

Mixing Ratios of the Uniformly Mixed Gases

Gas	Mixing Ratio (parts per million, by volume)
N_2	7.905×10^5
O_2	2.095×10^5
CO_2	330
CO	.075
N_2O	0.28
CH_4	1.6

(Ref 29:10)

The other class of gases consists of water vapor and ozone, which vary greatly in concentration with altitude, goegraphical location, and temperature. Hence, these two gases are treated separately when describing the atmosphere.

Note that no account is taken of other gases present in the atmosphere. There are, first of all, several other gases normally present in "uniformly mixed" proportions, such as the noble gases. None of these is present in large enough quantities to significantly affect absorption. There is also the problem of pollutants, such as hydrocarbons. These could, particularly in urban or industrial areas, result in significant absorption at particular wavelengths.

The very large number of possible species present in this sort of environment, and the virtual impossibility of

predicting just what mixture will be present in a given case, make accounting for this a virtual impossibility. In any case, the sort of situation in which these gases would be present in significant quantities would almost certainly be one in which particulate pollutants from the same sources would provide the predominant loss mechanism. Therefore, such gases are generally not considered, and are not included here.

Standard Atmospheres

In order to provide a common basis for atmospheric description, the U.S. Standard Atmospheric Supplements, 1956, and the Handbook of Geophysics and Space Environment (Ref 35) are generally used. These have been modified by AFGL to include water vapor and ozone densities (Ref 22). These models include pressure, temperature, density, and the densities of water vapor and ozone as a function of altitude. From the density, the number densities of the uniformly mixed gases can be calculated. Likewise, the number densities of water vapor and ozone can be calculated from their densities. These number densities are then used in calculating the effects of the gases on radiation.

The six models commonly used (especially by AFGL) are the 1962 U.S. Standard Atmosphere, Tropical, Midlatitude Summer (45° N, July), Midlatitude Winter (45° N, January), Subartic Summer (60° N, July), and Subartic Winter (60° N, January). Table III shows the U.S. Standard Atmosphere,

U.S. STANDARD ATMOSPHERE, 1962					
Ht. (km)	Pressure (mb)	Temp. (°K)	Density (g/m^3)	Water Vapor (g/m^3)	Ozone (g/m^3)
0	1.013E+03	288.1	1.225E+03	5.9E+00	5.4E-05
1	8.986E+02	281.6	1.111E+03	4.2E+00	5.4E-05
2	7.950E+02	275.1	1.007E+03	2.9E+00	5.4E-05
3	7.012E+02	268.7	9.093E+02	1.8E+00	5.0E-05
4	6.166E+02	262.2	8.193E+02	1.1E+00	4.6E-05
5	5.405E+02	255.7	7.364E+02	6.4E-01	4.5E-05
6	4.722E+02	249.2	6.601E+02	3.8E-01	4.5E-05
7	4.111E+02	242.7	5.900E+02	2.1E-01	4.8E-05
8	3.565E+02	236.2	5.258E+02	1.2E-01	5.2E-05
9	3.080E+02	229.7	4.671E+02	4.6E-02	7.1E-05
10	2.650E+02	223.2	4.135E+02	1.8E-02	9.0E-05
11	2.270E+02	216.8	3.648E+02	8.2E-03	1.3E-04
12	1.940E+02	216.6	3.119E+02	3.7E-03	1.6E-04
13	1.658E+02	216.6	2.666E+02	1.8E-03	1.7E-04
14	1.417E+02	216.6	2.279E+02	8.4E-04	1.9E-04
15	1.211E+02	216.6	1.948E+02	7.2E-04	2.1E-04
16	1.035E+02	216.6	1.665E+02	6.1E-04	2.3E-04
17	8.850E+01	216.6	1.423E+02	5.2E-04	2.8E-04
18	7.565E+01	216.6	1.216E+02	4.4E-04	3.2E-04
19	6.467E+01	216.6	1.040E+02	4.4E-04	3.5E-04
20	5.529E+01	216.6	8.891E+01	4.4E-04	3.8E-04
21	4.729E+01	217.6	7.572E+01	4.8E-04	3.8E-04
22	4.047E+01	218.6	6.451E+01	5.2E-04	3.9E-04
23	3.467E+01	219.6	5.500E+01	5.7E-04	3.8E-04
24	2.972E+01	220.6	4.694E+01	6.1E-04	3.6E-04
25	2.549E+01	221.6	4.008E+01	6.6E-04	3.4E-04
30	1.197E+01	226.5	1.841E+01	3.8E-04	2.0E-04
35	5.746E+00	236.5	8.463E+00	1.6E-04	1.1E-04
40	2.871E+00	250.4	3.996E+00	6.7E-05	4.9E-05
45	1.491E+00	264.2	1.966E+00	3.2E-05	1.7E-05
50	7.978E-01	270.6	1.027E+00	1.2E-05	4.0E-06
70	5.520E-02	219.7	8.754E-02	1.5E-07	8.6E-08
100	3.008E-04	210.0	4.989E-04	1.0E-09	4.3E-11

(Ref 22)

Table III. U.S.Standard Atmosphere (1962)

Table IV

Model Atmosphere Sea Level Values

Model	Pressure (mbar)	Temp (^{o}K)	Water Vapor (g/m^3)	Ozone (g/m^3)
U.S. Stand	1013.	288.1	5.9	5.4 E-05
Tropical	1013.	300.0	19.0	5.6 E-05
Mid-Lat Sum	1013.	294.0	14.0	6.0 E-05
Mid-Lat Winter	1018.	272.2	3.5	6.0 E-05
Sub-Arctic Sum	1010.	287.0	9.1	4.9 E-05
Sub-Arctic Winter	1013.	257.1	1.2	4.1 E-05

1962, as an example of the models. A comparison of the sea level values is given in Table IV as an indication of the readily available range of predictions. The water vapor density in the U.S. Standard atmosphere corresponds to approximately 50% relative humidity, while the other five all represent about 80% relative humidity at sea level. The altitude dependence of humidity also differs (Ref 29:9). Proper selection of an atmospheric model is therefore particularly important whenever concerned about an area of the spectrum where absorption by water vapor may be significant.

Molecular Scattering

The scattering, as stated in Chapter II, is essentially Rayleigh scatter, and can be described by the formula

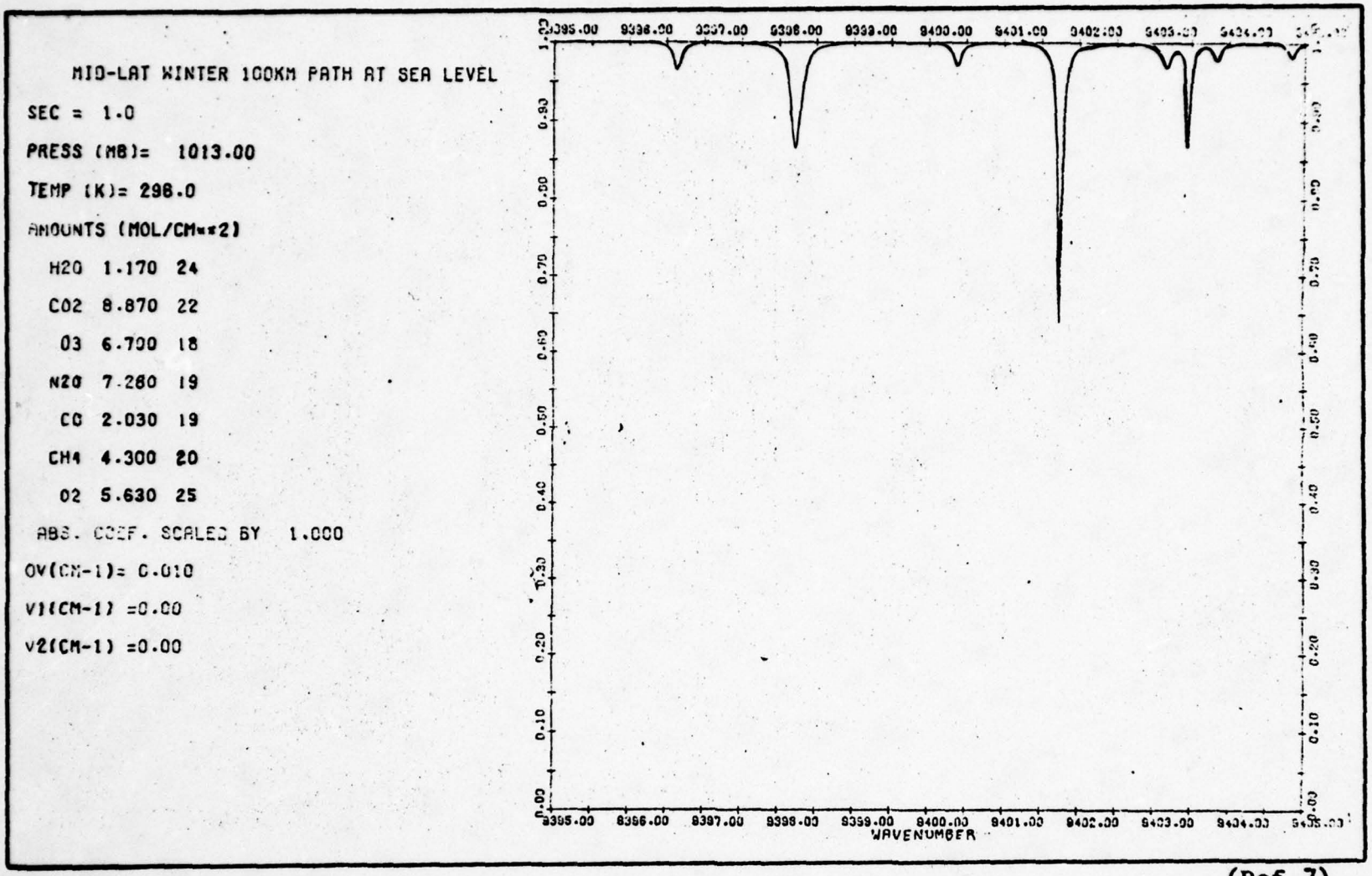
$$\sigma_m = (9.87 \times 10^{-20}) \times \nu^4 \qquad (7)$$

where $\nu = \frac{1}{\lambda}$ is the wavenumber of the radiation. The constant in this formula is an empirical one, obtained from LOWTRAN 3 (Ref 29:11). This calculation is performed in a subroutine called RAYLEE, even though it is essentially only one step long. This is done to be consistent with the other calculations.

Molecular Absorption

The problem of molecular absorption is much more difficult to handle. The Air Force Geophysical Laboratory has developed several computer codes designed to calculate the molecular absorption. The results of one of these programs (Ref 7) in the area of the 1.06μ wavelength, is shown in Fig. 4. Transmittance is plotted as a function of frequency (in cm^{-1}). The laser line center frequency is almost exactly 9400.2 cm^{-1}, and the width of the laser line is approximately 3 cm^{-1}. This calculation was made for a midlatitude winter standard atmospheric model and for a range of 100 km, in order to show the weak absorption lines present in the atmosphere in this wavelength region.

For both the 1.06μ and .53μm beams, the absorption coefficient is set equal to .001, corresponding to a transmittance in excess of 99% for a 10 km path. This is based upon the calculations from the AFGL programs. All of these programs, as described in Appendix C, require significant amounts of computer core space and processor time, in addition to lengthy files of molecular absorption line parameters. Therefore,



(Ref 7)

Fig. 4. Results of Program HIRACC

this figure has been set in as a conservative measure of the absorption.

The absorption coefficient for the dye laser beam is also set to .001, since there is very little absorption over most possible wavelengths, and the calculations necessary to obtain exact values are excessive. As a cautionary note, however, it should be understood that there can be significant absorption in the wavelengths between the visible and the 1.06 micron beam. In particular, there is significant absorption around .70 microns, .83 microns, and between .89 and .99 microns (Ref 20). As new dyes become available, these absorption problems must be evaluated. The program is set up to flag any wavelength in these regions, warning that more detailed calculations of absorption are required.

A factor which may be of importance for laser beams of very narrow optical bandwidth, when calculating molecular absorption, and which can generally be ignored for any of the other calculations, is that of precisely defining the wavelength. All the absorption compilations are based upon wavenumbers, which is essentially a frequency and hence independent of medium. The reciprocal of wavenumber, however, gives the vacuum wavelength of the radiation. In contrast, laser manufacturers generally specify the wavelength as determined by laboratory measurements of wavelength in air. Hence, the reciprocal of 1.0638 microns would lead to a wavenumber of 9400.26 cm^{-1}. If the actual vacuum wavelength is (1.0638) x (1.0004) = 1.0642 microns, the corresponding

actual wavenumber is 9396.50 cm^{-1}. This is more than enough difference to move from the far wings of an absorption line to the peak. In the case of a laser such as the Nd:YAG, the linewidth of the transition is on the order of 3 cm^{-1} at room temperature (Ref 32:362), so that the presence of one or two small narrow absorption lines may safely be ignored and there is no need to be concerned with the wavelength ambiguity.

IV. Modeling of Aerosol Effects

As has been stated above, it is, in principle, possible to accurately calculate the total aerosol attenuation for the case of single scatter, given the distribution of aerosol particle sizes and complex refractive indices. Some of the recent work on determining and modeling aerosol distributions will be discussed and the simplifying approximations used in the present model will be described.

Atmospheric Models

Despite considerable effort by many researchers over the past several decades, there is still no reliable method of predicting the particular distribution of aerosol concentration to be found on a given day (Ref 31). Indeed, there is no way of knowing this distribution even when given a full set of meteorological data as normally reported. Many different aerosol distributions could lead to the same reported visibilities.

This lack of precise information concerning the particle distribution has led to many attempts to develop models of the "typical" atmosphere (Refs 28, 29, 31).

The Air Force Cambridge Research Laboratories (AFCRL) (now renamed the Air Force Geophysical Laboratory) has continuously worked on improving and updating these aerosol models. The latest generation of these models was published

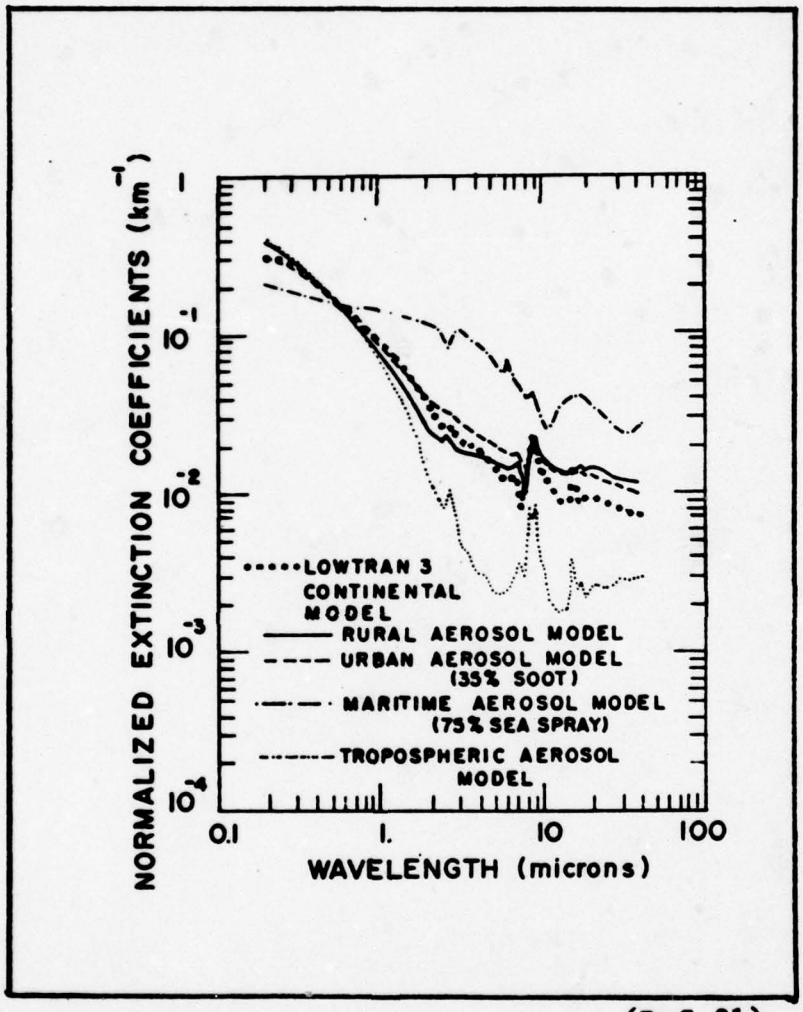
in 1976 (Ref 31). This series of models consists of three boundary layer (up to 2 kilometer altitude) models, two upper troposphere models, four stratosphere models, and two upper atmosphere models.

For the case of near-earth, nearly horizontal paths, only the boundary layer models are considered. These three models are the rural, urban, and maritime models. The rural model represents the aerosol conditions found in continental areas not influenced by urban or industrial areas. The aerosol is assumed to be composed of 70% water soluble and 30% dustlike particles.

The urban model differs in that sootlike particles are assumed to be added to the rural mixture, in the form mostly of combustion products. These carbonaceous particles are assumed to comprise 35% of the distribution.

The maritime model includes salt particles which result from sea spray evaporation. This model is incomplete in that it does not take windspeed and relative humidity into account. These variables can be important in the first 100 meters or so above the surface.

Using these three models for the particle distributions, Mie's scattering theory was used to determine the details of the scattering and absorption. For the present purposes, only the behavior of the overall aerosol extinction coefficient is of interest. Fig. 5 shows the aerosol extinction coefficient as a function of wavelength.



(Ref 31)

Fig. 5. Aerosol Extinction vs. Wavelength

Simplifying Assumptions

Over the wavelength range of interest (.5 microns to 1.06 microns) the three curves can be approximated by the straight lines, as shown in Figs. 6-8. These lines correspond to the following expression

$$\sigma_a = C \lambda^{-D} \qquad (8)$$

where the parameters C and D have the following values

Table V

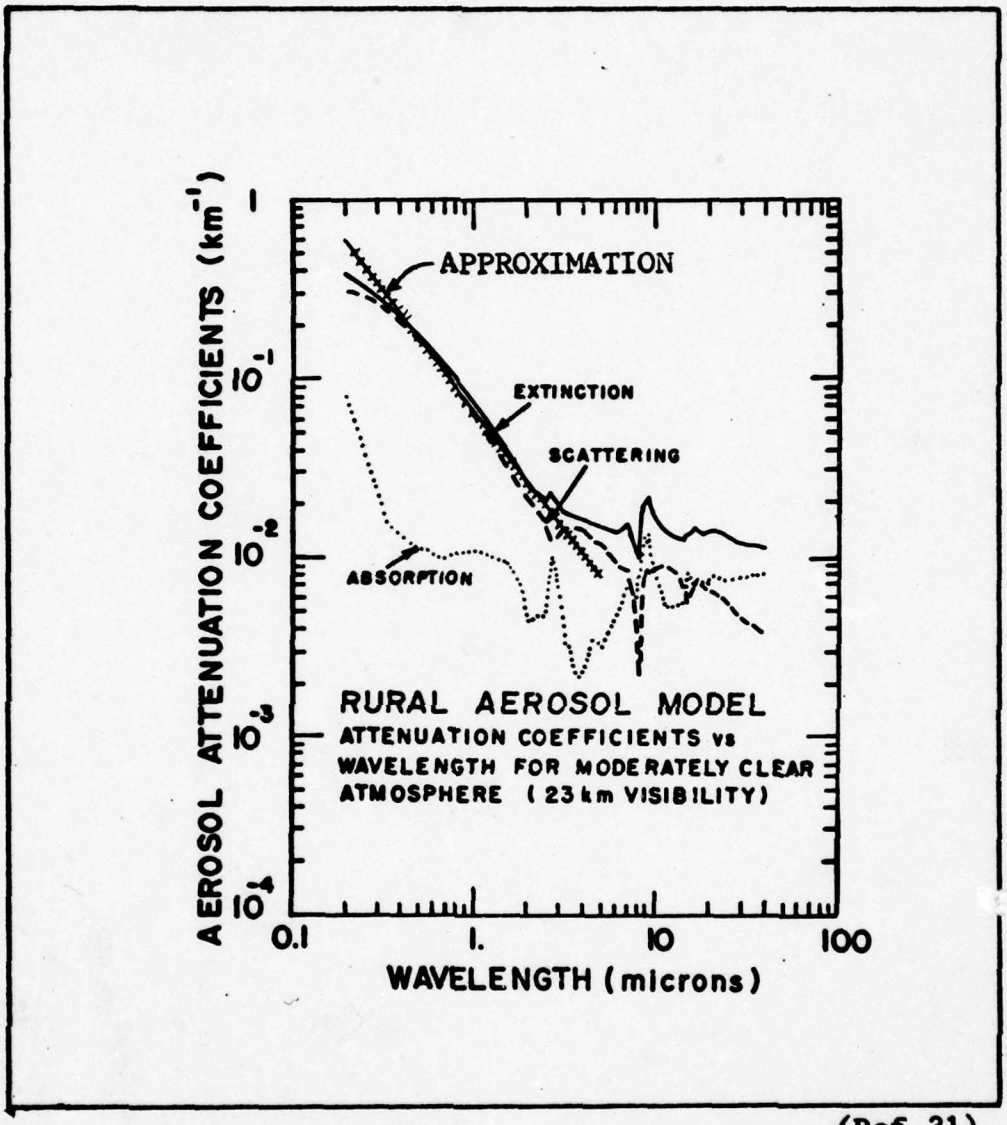
Coefficients for Aerosol Approximations

Model	C	D
Rural	0.077	1.21
Urban	0.088	0.98
Maritime	0.141	0.196

These approximations are used in the subroutine AROSOL for the aerosol extinction coefficients corresponding to a visibility of 23 kilometers. These expressions give extinction coefficients within 2% of those calculated from the exact models, as incorporated in LOWTRAN 3B (Ref 30).

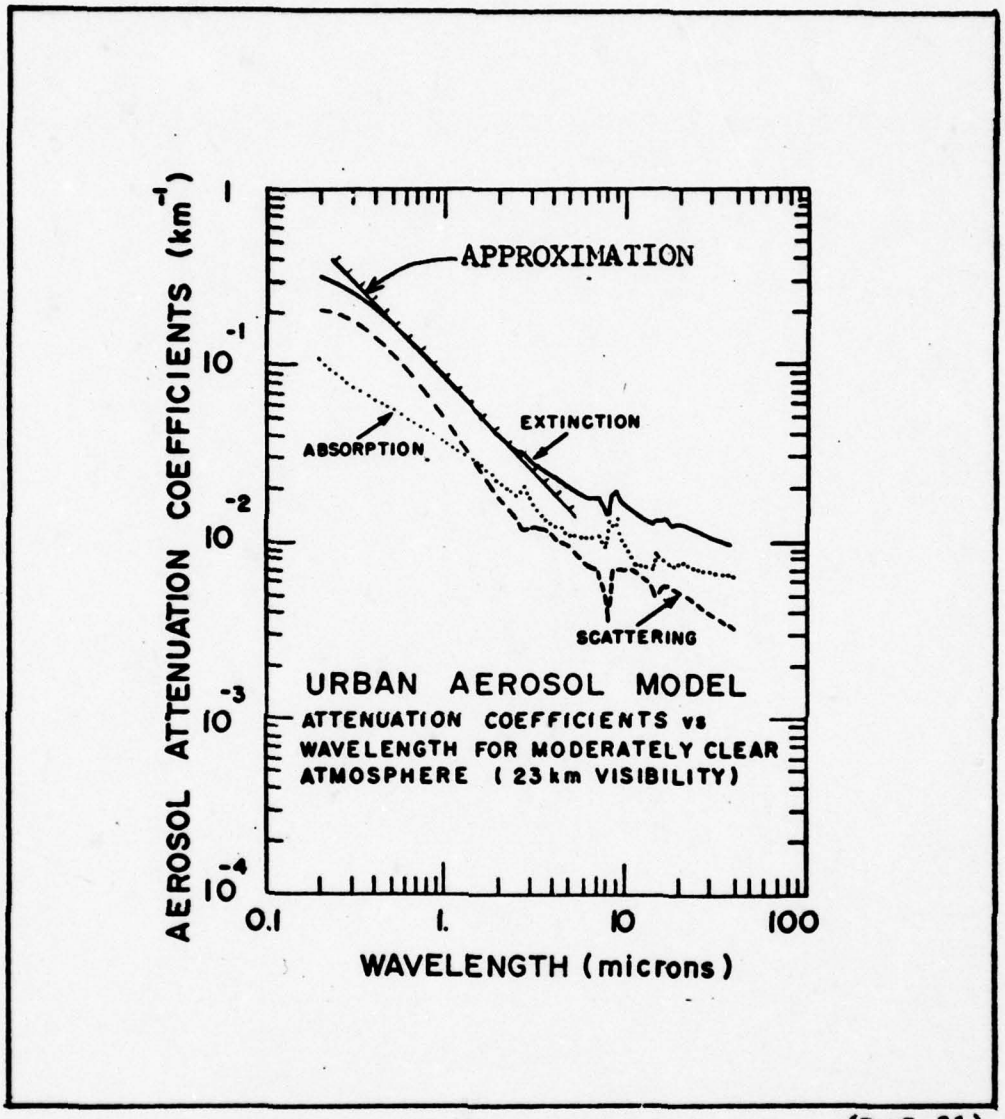
The interpolation scheme used for other visibilities is that found in LOWTRAN 3 (Ref 29:14). There it is found that

$$N(z) = \frac{a(z)}{VIS} - b(z) \qquad (9)$$



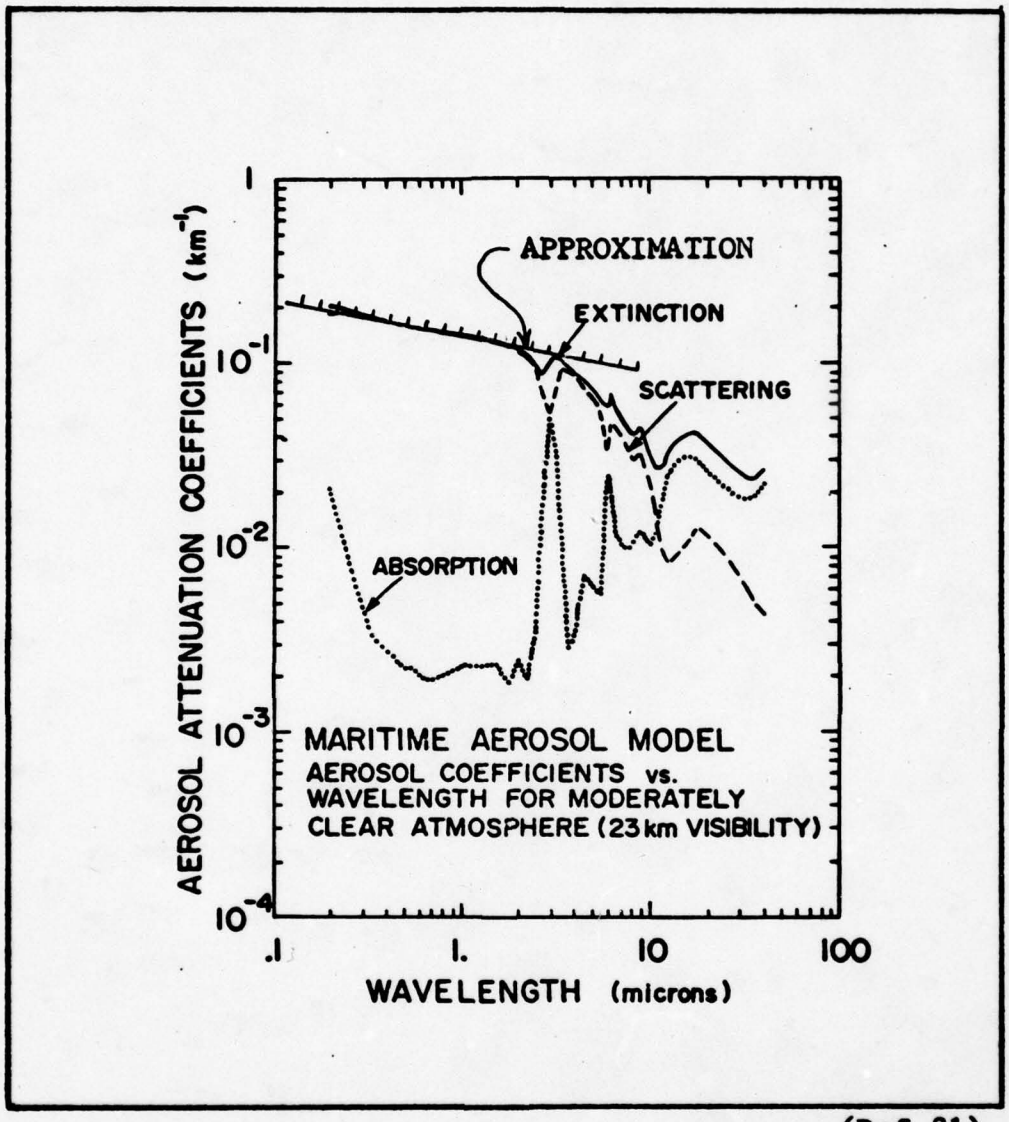
(Ref 31)

Fig. 6. Aerosol Extinction Approximation (Rural Model)



(Ref 31)

Fig. 7. Aerosol Extinction Approximation (Urban Model)



(Ref 31)

Fig. 8. Aerosol Extinction Approximation (Maritime Model)

where N(z) is the aerosol number density which is a function of altitude and is proportional to the aerosol extinction coefficient σ_a.

The procedure used for this interpolation in LOWTRAN is based upon a tabulation of N at 1 kilometer altitude intervals, for visibilities of 5 and 23 kilometers. For the altitudes of interest a and b are calculated from Eq (9) above and then the value of σ_a is calculated. For the present model, only the ground level number densities are used, yielding

$$\sigma_{a_{VIS}} = \frac{\sigma_{a_{23}}}{2.83 \times 10^{3}} \times \left(\frac{6.9894 \times 10^{4}}{VIS} - 2.089 \times 10^{2} \right) \quad (10)$$

It should be noted that both in LOWTRAN and in this analysis the number densities used are those for the "average continental aerosol model," which was a preliminary version of the rural model used in LOWTRAN 3B (Ref 30). This should introduce no significant errors into the calculation, however.

The AROSOL subroutine also includes provision for a non-standard model of the aerosol distribution. This is accomplished by entering new values for C and D, the parameters as found in Table V. This, of course, assumes that the new distribution can also be approximated by a straight line on the log-log plot as in Fig. 5. Note that this would allow the subroutine to be used in other wavelength intervals, anomalous refractive indices around 6-10 microns wavelength are avoided.

V. Modeling of Turbulent Effects

Several very basic assumptions are made concerning the nature of the turbulent effects. The first is that the interaction of the beam with the turbulent eddies falls into the inertial subrange of turbulence. This requires that the Reynolds number be high enough so that there is a significant gap between the size scales where energy is introduced into the atmosphere and where it is viscously dissipated. Tatarskii (Ref 34:51-59) discusses this requirement, along with the detailed description of the scale lengths. Lawrence and Strohbehn (Ref 17:1526-1527) discuss the turbulence parameters as well. From their discussion, the inner and outer scale lengths have been chosen as 1 mm and 50 meters, respectively. Hence, all the significant turbulent eddies are assumed to have sizes between 1 mm and 50 meters.

The laser beam is assumed to have the initial form of a Gaussian beam.

$$E_o(0, \rho) = A \exp\left[- \left(\frac{2}{D^2} + \frac{ik}{2F}\right)(\rho^2)\right] \qquad (11)$$

where D is the diameter of the beam and F is the radius of curvature of the wavefront.

After reflection from the target, the beam is assumed to have the same form. This has been chosen as generally reasonable for any size target, even though reflection from

a small corner cube may more nearly resemble a uniform small source, which could be treated as a point source of spherical waves.

At the target plane (and receiver plane for the reflected beam) the beam is assumed to have an instantaneous Gaussian shape, with size parameters discussed below under beam wander.

Turbulence Strength

The parameter C_N^2, called the refractive-index structure parameter, is the measure of the strength of turbulence. C_N^2 has units of meters $^{-\frac{2}{3}}$. It is actually a measure of the difference in refractive-index between two nearby points. Actual measurements of the parameter are always done indirectly, at least in the optical wavelength range. It is either done by observing the optical turbulence effects and going back to calculate C_N^2, or by taking measurements of C_T^2, the equivalent parameter for temperature variations. The value of C_N^2 can then be simply related to C_T^2 by the formula (Ref 34:102)

$$C_N^2 \cong \left(\frac{80 \times 10^{-6} p}{T^2}\right)^2 C_T^2 \qquad (12)$$

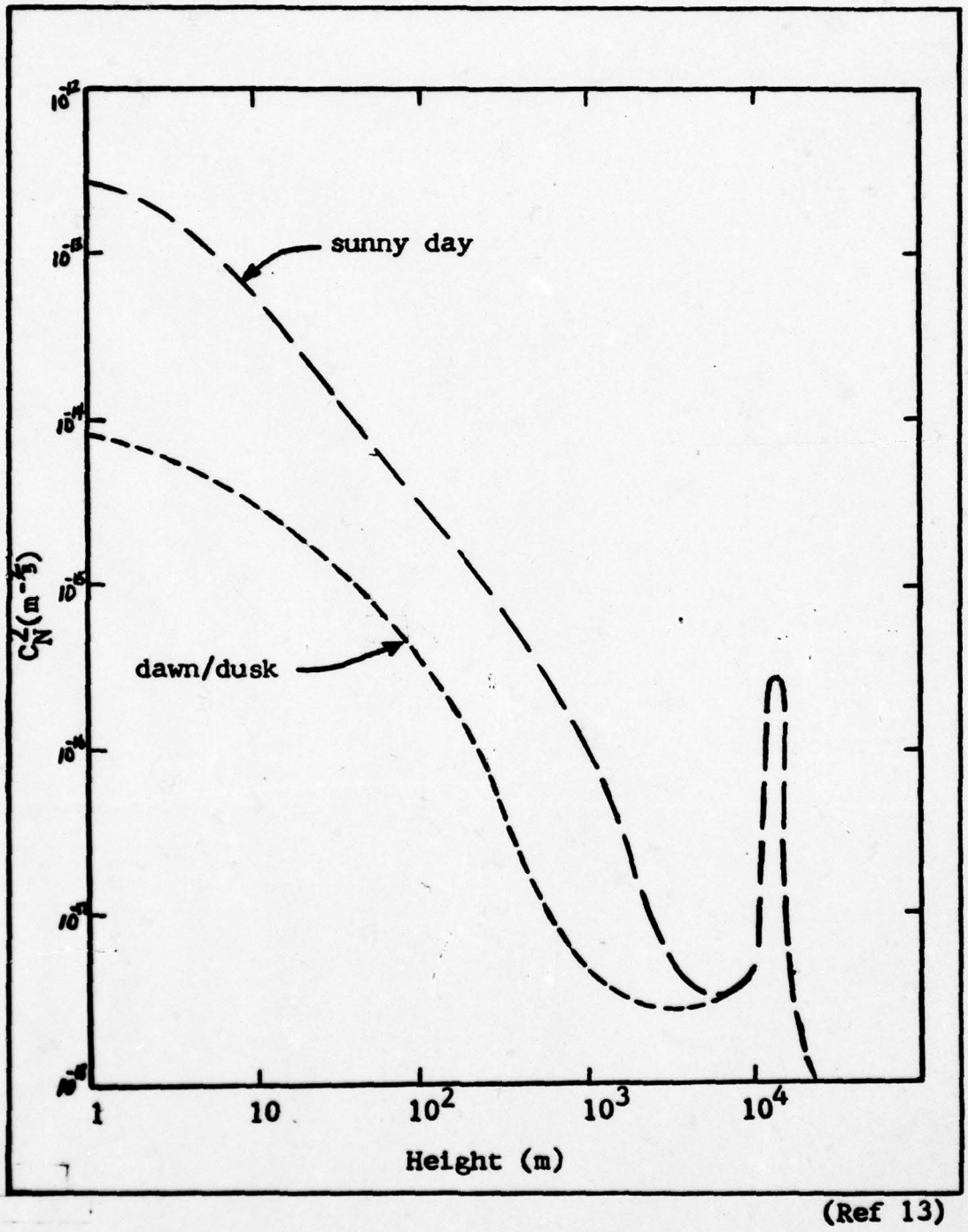
where the numerical coefficient of 80 is actually slightly wavelength dependent.

In general, C_N^2 is strongly dependent upon position and altitude. Various expressions have been used to express C_N^2 as a function of altitude (actually height above ground). A common model is that of Hufnagel (Ref 13) which is presented

in graphical form (Fig. 9) rather than as an analytic model. It can be readily seen that the weather conditions strongly affect the value, as do time of day and altitude. Rather than using a particular analytic function or tabulating data for the curves of the Hufnagel model, an "effective value" of C_N^2 is used in this model. A value of C_N^2 is selected as representative of the path as a whole and treated as a constant in the calculations. The default value is set to 5.0×10^{-15}, which can be seen to correspond to a very low value at the surface but a high value at a height of one hundred meters, hence not unreasonable for the entire path. Since this choice is clearly arbitrary, it can be varied to fit the results of measurements.

Beam Wander

The phenomenon of beam wander is treated as described by Fante (Ref 10:18-24). The beam is assumed to have an instantaneous Gaussian cross-section at the target (or receiver) plane. The short term beam radius ρ_s is defined as the radius at which the short term average irradiance is reduced by a factor of e^{-1} from the maximum. In general, then, this short term spot will be deflected by the large eddies in the beam. The long term average irradiance will therefore be spread over a larger area. The e^{-1} point of this distribution is defined as ρ_L. Another parameter ρ_c is defined as the measure of the deflection, or beam centroid



(Ref 13)

Fig. 9. Refractive Index Structure Factor, Typical Values

wander, where

$$\rho_c^2 = \rho_L^2 - \rho_s^2 \tag{13}$$

Then, using the waveform of Eq (11), it can be shown (Ref 10:21) that

$$\langle \rho_L^2 \rangle \cong \frac{4x^2}{k^2 D^2} + \frac{D^2}{4}\left(1 - \frac{x}{F}\right)^2 + \frac{4x^2}{k^2 \rho_o^2} \tag{14}$$

for $x \ll (k^2 C_N^2 \ell_o^{5/3})^{-1}$

and

$$\langle \rho_L^2 \rangle \cong \frac{4x^2}{k^2 D^2} + \frac{D^2}{4}\left(1 - \frac{x}{F}\right)^2 + \frac{2.2\, x^3 C_N^2}{\ell_o^{1/3}} \tag{15}$$

for $x \gg \left(k^2 C_N^2 \ell_o^{5/3}\right)^{-1}$

where, as usual, k is the wavenumber $2\pi/\lambda$ and ρ_o is defined as

$$\rho_o = (.626\, k^2\, x\, C_N^2)^{-3/5} \tag{16}$$

The first two terms in each of the above expressions make up the vacuum beam spread (VBS in the program) and the third term is the turbulent contribution.

The calculation of ρ_s and ρ_c is not so straightforward. There are four different combinations of length parameters which lead to different expressions for the short term effects. These depend upon the coherence length ρ_o, defined

above; beam diameter D; outer scale of turbulence L_o; range x; wavenumber k and L, where L is the smaller of ρ_o and D. It is also assumed that $D > \ell_o$.

Case 1. If $\rho_o \ll D < L_o$ and $x \leq kL^2$, then

$$\langle \rho_s^2 \rangle \simeq \text{VBS} + \frac{4x^2}{k^2 \rho_o^2} \left[1 - 0.62 \left(\frac{\rho_o}{D} \right)^{\frac{1}{3}} \right]^{\frac{6}{5}} \tag{17}$$

and

$$\langle \rho_c^2 \rangle \simeq \frac{2.97\, x^2}{k^2\, \rho_o^{\frac{5}{3}}\, D^{\frac{1}{3}}} \tag{18}$$

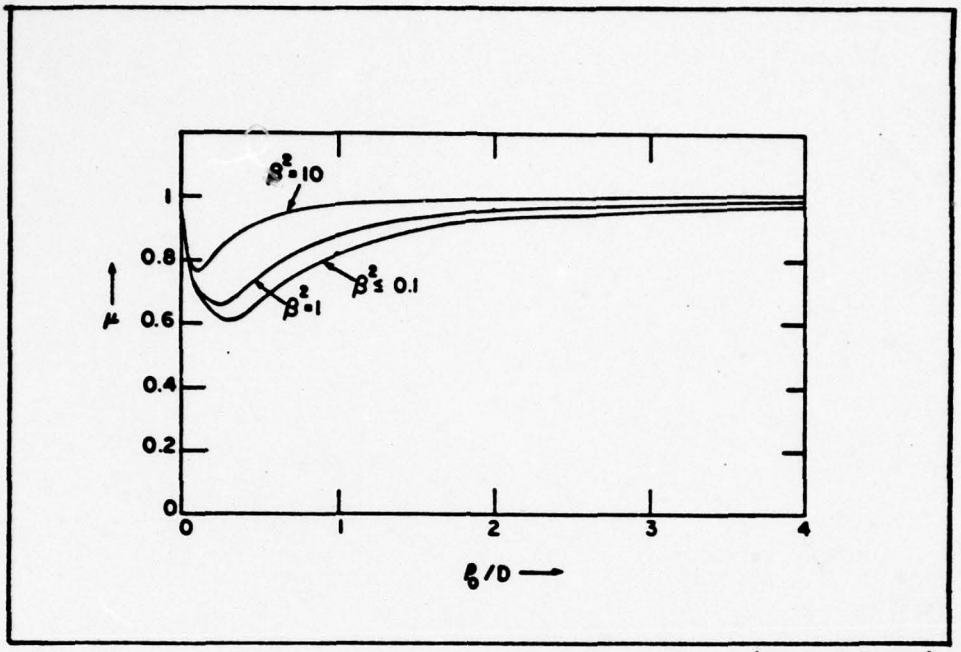
Case 2. If $\rho_o \approx D$ and $x \leq kL^2$, there are no simple expressions for ρ_s and ρ_c. Fante (Ref 10: 23-24) gives a graphical solution in terms of a parameter β, where

$$\beta^2 = \left(\frac{kD^2}{4x} \right)^2 \left(1 - \frac{x}{F} \right)^2 \tag{19}$$

The graphical solution leads to a value of μ where

$$\mu = \left[\frac{\langle \rho_s^2 \rangle}{\langle \rho_L^2 \rangle} \right]^{\frac{1}{2}} \tag{20}$$

In the computer model, the graphical solution has been approximated by storing values of the three plotted curves (Fig. 10) in a two dimensional array (RATIO) and using an



(Ref 10:24)

Fig. 10. Parameters for Beam Wander Calculation

interpolation scheme to find μ. Then ρ_s is calculated from Eq (17), and ρ_c from Eq (13).

Case 3. If $\rho_o >> D$ and $x \leq kL^2$, beam wander is negligible and $\rho_s \approx \rho_L$. This corresponds to short ranges (a few hundred meters) or weak turbulence.

Case 4. If $x >> kL^2$, the beam breaks up into multiple patches. The instantaneous pattern consists of several spots, and the beam centroid wander is negligible. An

approximate expression for ρ_c (Ref 10:23) is available for $x \gg kD^2$ and $D \gg \rho_o$.

$$\langle \rho_c^2 \rangle \approx C_N^{\frac{6}{5}} k^{-\frac{1}{5}} x^{\frac{3}{5}} \qquad (21)$$

This expression has been used here for ρ_c in all cases for $x > kL^2$. In this case, ρ_s has no well defined meaning. It has been arbitrarily set equal to $\sqrt{VBS}$, which is the vacuum beam spread. Clearly, the numbers resulting from calculations using this case are suspect. The calculations above give no idea as to the number of beams or their locations, only that the root mean square radius of the area where they form is ρ_L. A rather arbitrary cutoff of $\rho_L > 1.5\ \rho_s$ was set in the program to warn that beam breakup is causing serious spreading of the long term average. This means that the short term prediction of irradiance on axis is questionable, and is probably more variable on a pulse-to-pulse basis than the calculated results indicate.

These four cases are considered and ρ_L, ρ_s, and ρ_c are calculated in subroutine AXIAL. The mean irradiance and characteristic time of beam wander (WNDTIM) are also calculated in AXIAL.

Temporal Behavior of Beam Wander. The entire treatment of turbulence has been based upon an assumption of the "Taylor frozen flow hypothesis." This is the assumption that the turbulence encountered by the beam is in the form of small cells which do not change while they are seen by the beam. Rather, the changes in turbulence are due to the flow of such cells across the beam (Ref 34:88-91). Clearly, then, for the case of beam wander being considered, the deflection or spreading of the beam can be expected to change on a time scale of D/V, where D is the beam diameter and V is the transverse wind velocity. Neither of these parameters is a constant for the case of a diverging beam in the real atmosphere. An average value of V is one of the input parameters. The value of D used is the initial beam diameter at the transmitter for the forward beam and target diameter for the reflected beam. This gives the shortest time scale of changes to be expected.

It is to be noted that for reasonable values of D and V, these characteristic times (Table VI) are of the same order of magnitude or less than the pulse repetition time for a low duty cycle pulsed laser (3×10^{-2} seconds). This means that the wander effect can be expected to change from one pulse to the next. The times are long compared to the length of a single pulse (10^{-8} seconds), however, so that each sees essentially a single set of cells. Thus, there is no time averaging within each pulse, and successive pulses see uncorrelated turbulence cells.

Table VI

Characteristic Time Scale of Beam Wander

D (m)	V (m/sec)	(v) (knots)	Wander Time Scale (seconds)
.01	1	(1.9)	1×10^{-2}
.01	2	(3.9)	5×10^{-3}
.01	3	(5.8)	3×10^{-3}
.01	5	(9.7)	2×10^{-3}
.10	2	(3.9)	5×10^{-2}

Mean Irradiance

The calculation of the mean irradiance on axis at a distance x from the transmitter (or reflector) starting with the basic electromagnetic wave equation is possible using Fourier transform techniques (Ref 10:24-25). This involves assuming a form for the wavenumber spectrum of the index of refraction fluctuations and for the input waveform. This wavenumber spectrum is discussed below since it is required when considering the irradiance scintillations. For the present calculation, a simpler approach is taken.

A Gaussian input beam is assumed. In terms of the wander description above, it is assumed that, since all refractive-index differences are small, so are the deflections. In terms of the more mathematical treatment (Ref 34) which treats all of turbulence as a scattering from random inhomogeneities, the equivalent assumption is that, since $\ell_o \gg \lambda$,

essentially all the scattering is in the forward direction.

In either case, the result of the assumption is that all of the transmitted power (after molecular and aerosol losses are accounted for) reaches the target plane. The spatial distribution is assumed to be Gaussian. The value of ρ_L calculated above is taken as the e^{-1} radius for the distribution. Hence, if A is the peak irradiance, the distribution is assumed to be

$$E_e(\rho) = A \exp[-(\rho/\rho_L)^2] \tag{22}$$

and the total power in the target plane is

$$P_T = \int_{\substack{\text{total} \\ \text{area}}} E_e(\rho)\, d(\text{area}) = 2\pi \int_o^\infty \rho\, E_e(\rho)\, d\rho \tag{23}$$

$$P_T = 2\pi A \int_o^\infty \rho \exp[-(\rho/\rho_L)^2]\, d\rho \tag{24}$$

$$P_T = \pi A \rho_L^2 \tag{25}$$

Using the conservation of energy argument as stated above, this is set equal to the input power, after attenuation, and solved for A, the average irradiance on axis (called AXINT in the program).

Irradiance Scintillations

By far the largest effect of turbulence on these diverging beams is the scintillation effect. Any beam which

passes through more than a few meters of turbulent atmosphere suffers redistribution of its energy. The observed irradiance then displays fluctuations which are called scintillations. The phenomenon has been studied both experimentally and theoretically. Tatarski's work (Ref 34) is the standard reference on the basic theory. He also includes a great deal of comparison of theory with the experimental data which was available.

The theoretical treatment (Ref 34:166-290) is essentially complete for plane and spherical waves, although approximations are necessary in order to solve the equations. It is first assumed that the scalar wave equation can be used, rather than the full vector equations. This requires that polarization effects be insignificant. This is a quite good assumption for $\lambda << \ell_o$. The wave equation then takes the form

$$\nabla^2 \psi + k^2(1 + \epsilon_1) \psi = 0 \qquad (26)$$

where ψ is the field, k the wavenumber and ϵ_1 the small random part of the permittivity.

The scalar wave equation is then solved using the method of smooth perturbations, and using what is generally called the Rytov approximation. In this case, the scalar wave equation is rewritten in terms of Φ, the log of ψ.

$$\nabla^2 \Phi + (\nabla \Phi)^2 + k^2 + k^2\epsilon_1 = 0 \qquad (27)$$

This non-linear equation cannot be solved exactly and contains the random function ϵ_1. The equation is solved by a perturbation method in powers of ν, where $\nu = \sqrt{\langle \epsilon_1^2 \rangle}$.

After considerable effort, it is shown that the result can be considered as a case of multiple scattering from the random inhomogeneities of the medium. After making several approximations which limit the range of applicability of the results, expressions for the variance in the log-amplitude are obtained. The log-amplitude is related to Φ by the expression $\Phi = \chi + iS$; i.e., $\chi = \mathrm{Re}(\Phi)$. The expression for the so called log-variance are:

Plane wave:

$$\sigma_x^2 = .308\, C_N^2\, k^{\frac{7}{6}}\, x^{\frac{11}{6}} \tag{28}$$

Spherical wave:

$$\sigma_x^2 = .124\, C_N^2\, k^{\frac{7}{6}}\, x^{\frac{11}{6}} \tag{29}$$

The conditions for validity of the above expressions include:

$$\lambda x \gg \ell_o$$

$$k^{\frac{7}{6}}\, x^{\frac{11}{6}}\, L_o^{-\frac{2}{3}} \gg 1$$

and

$$\lambda^3 x \ll \ell_o^4$$

Tatarskii then states (Ref 34:258) that experimental evidence indicates that his results, as above, are justified for $\sigma_x < 0.8$.

Many workers have continued the theoretical work and experiment verification. Lawrence and Strohbehn (Ref 17) summarized the status of investigation into the probability distribution of irradiance and the calculation of the log-variance in 1970. They tabulate the formulas available for calculation of the log-variance under various assumptions. Listed below are only those pertaining to this study. A homogeneous medium is assumed, calling for the choice of an effective value of C_N^2. The Kolmogorov spectrum is again assumed. Ranges are assumed to be such that $x >> \ell_o^2/\lambda$, which is not very restrictive. The beam wave formula is from Ishimaru (Ref 14). The equations here are for the log-variance of irradiance (variance in the log of irradiance), rather than amplitude. These are simply related by the fact that the irradiance is just the square of the amplitude, so that

$$\sigma_{\ln_I}^2 = 4\,\sigma_x^2 \tag{30}$$

This $\sigma_{\ln I}^2$ is the LOGVAR used in the program, and is hereafter called σ^2.

Plane wave:

$$\sigma^2 = 1.23\, C_N^2\, k^{7/6}\, x^{11/6} \tag{31}$$

Spherical wave:

$$\sigma^2 = 0.50\, C_N^2\, k^{7/6}\, x^{11/6} \tag{32}$$

Gaussian beam wave:

$$\sigma^2 = 4\pi^2(0.033\, C_N^2)\Gamma(-5/6)k^{7/6} x^{11/6}$$

$$\left[\frac{\alpha_1 x}{1+\alpha_1 x}\right]^{5/6}\left[\frac{3}{8}{}_1F_1\left\{-\tfrac{5}{6}, 1; \frac{2\rho^2}{w_o^2[1+(\alpha_1 x)^2]}\right\} - g(\alpha_1 x)\right] \qquad (33)$$

where w_o = initial beam radian (DIAM/2)

$\alpha_1 = \lambda/(\pi w_o^2)$

${}_1F_1(a,c;z)$ is the Kummer function

$$g(\alpha_1 x) = \mathrm{Re}\left[\frac{6}{11}\left(\frac{1+i\alpha_1 x}{i\alpha_1 x}\right)^{5/6} {}_2F_1\left(-\frac{5}{6}, 1; \frac{17}{6}; i\alpha_1 x\right)\right]$$

${}_2F_1(a,b;c;z)$ is the hypergeometric function.

As currently set up, the program calculates the log-variance for the Gaussian beam wave case. The distance ρ is the distance off the axis of the beam at which the log-variance is calculated. Only the on-axis case is considered, so that $\rho = 0$.

Experimental results have indicated that the log-variance saturates at a value of about 2.4, and indeed decreases slightly (Ref 17:1524). Fante (Ref 10:34-35) discusses briefly, and gives extensive references to, the large volume of effort which has gone into explaining the behavior in strong turbulence. He then presents an approximate formula for the log-variance in strong turbulence.

$$\sigma_I^2 = 1 + \frac{0.99}{\left(\sigma_1^2\right)^{5/5}} \qquad (34)$$

where σ_I^2 is the normalized variance in the irradiance, σ_1^2 is the plane wave solution above (Eq 31), and strong turbulence is defined as existing when $\sigma_1 >> 1$. It is easy to show that

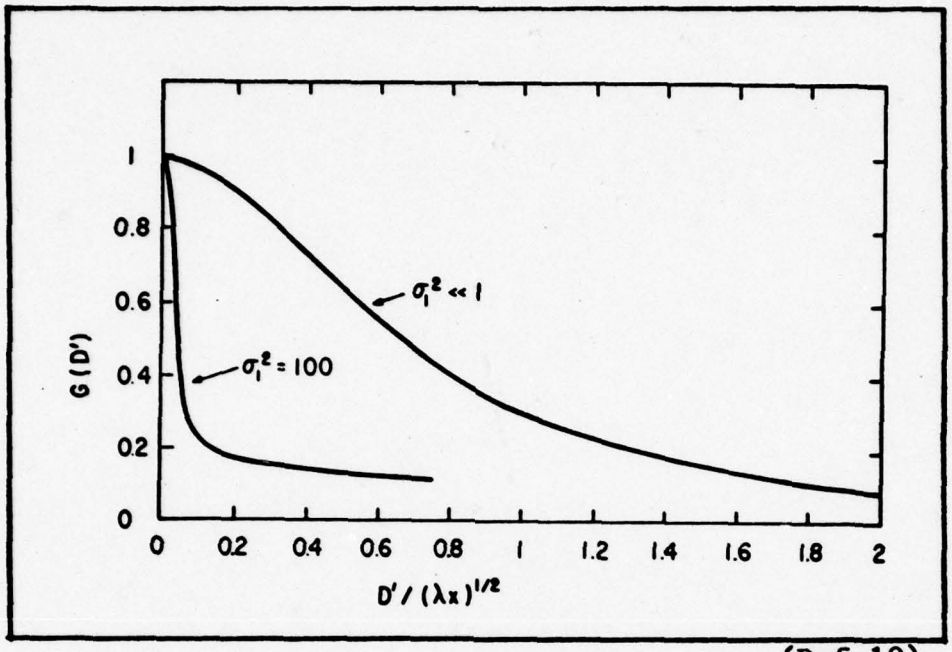
$$\sigma^2 = \ln(1 + \sigma_I^2) \tag{35}$$

This gives a plane wave solution for strong turbulence. The effects of scintillation are stronger on a plane wave than on a beam or spherical wave, so that the calculated log-variance will be stronger than is appropriate. This should be a relatively minor effect and will in some measure compensate for the large variation in irradiance due to beam breakup in strong turbulence which is not adequately accounted for. The empirical formula is used for $\sigma_1^2 > 1.8$, which is approximately where $\sigma_I^2 = \sigma_1^2$ in the formula.

Aperture Averaging

The fluctuations σ^2 calculated previously apply strictly speaking only to a point receiver. Any finite receiver will see, not σ^2, but an average of the fluctuations over the aperture. The appropriate average involves integrating the amplitude (or irradiance) covariance functions, which have not been included here, over the aperture. Fante presents a solution in graphical form (Fig. 11), in terms of aperture diameter D^1 (Ref 10:38-40). The function G is the ratio of observed fluctuations to those for a point aperture.

In the program, G (called APAV) has been approximated by a function which approximates the two curves of Fig. 11



(Ref 10)

Fig. 11. Aperture Averaging Approximations

quite well and is assumed to be better than an interpolation for an estimate in the intermediate region.

$$G = 0.09 + 0.91 \exp\left\{- 1.0\left[\frac{1}{.89}\left(\frac{D^1}{\lambda x}\right)^{\frac{1}{2}}\right]^{\frac{3}{2}}\left[1 + \sigma_1^2\right]\right\} \qquad (36)$$

Temporal Behavior of Scintillations

The scintillation behavior, like the wander effect, has a frequency spectrum which is a highly complex function of the irradiance. Fante (Ref 10:40-41) refers to several approximate solutions for the spectrum in various limits. It has been experimentally found that the width of the frequency spectrum can be expressed (at least in order of

magnitude) by simple expressions. The inverse of the width is taken as the characteristic time of scintillations (SCNTIM).

$$\text{for } \sigma_1^2 < 1 \qquad \text{SCNTIM} = \frac{(\lambda x)^{\frac{1}{2}}}{V} \tag{37}$$

$$\text{for } \sigma_1^2 > 1 \qquad \text{SCNTIM} = \frac{\rho_p}{V} \tag{38}$$

where $\rho_p = \frac{.36\ (\lambda x)^{\frac{1}{2}}}{(\sigma_1^2)^{\frac{1}{5}}}$ is a transverse correlation distance for the case of strong turbulence (Ref 10:37).

Probability Distribution of Irradiance

It is found theoretically, as a direct result of using the Rytov method of dealing with log of the amplitude as the fundamental variable, that the irradiance probability distribution is log-normal. This means that the log of the irradiance is normally distributed. Experimental results have shown good agreement with this distribution, within the limits of applicability of the Rytov method. The limit described by Fante (Ref 10:42) is that log-normality holds for $\sigma_1^2 < 0.3$. Purely on an empirical basis, it has been observed that the log-normal distribution is also a good approximation in the realm of $\sigma_1^2 > 25$.

In the intermediate regime, the expected probability distribution is by no means clear. Fante (Ref 10:43) discusses some of the distributions proposed. These include perturbed log-normal, Rice-Nakagami, Rayleigh and three-parameter truncated log-normal. It has recently been

proposed (Ref 3) that a normal distribution is the most nearly correct. A basic problem in experimental verification is the wide spread generally observed in the data. Many different distributions can usually be made to fit the data.

The distribution chosen here is the three-parameter truncated log-normal (Appendix D), following Davidson and Gonzales-del-Valle (Ref 9). This distribution gives an excellent fit to their data. The measurements were done in water in a carefully controlled experiment in the laboratory. They give no indication of the appropriate values of the offset parameter for use in the atmosphere, so it is arbitrarily picked as a small percentage (10^{-6}) of the mean irradiance. This should give reasonable results, since the observed distributions have generally been not too different from the two-parameter log-normal. The truncation point is clearly at zero irradiance, since no negative irradiance can be observed. This does not enter explicitly into the calculations, since the mean and variance are calculated separately.

The calculation of the irradiance probability distribution at the receiver is not just a matter of calculating the log-variance and mean of the irradiance. The values of log-variance and mean irradiance on axis at the target plane are first calculated. The beam wander parameters are then applied to determine the range of reflected power.

First, the irradiances on axis at the target corresponding to adding or subtracting the log-variance to the

log of the mean irradiance are calculated, in subroutine TURB. For the strong turbulence case, where σ_1^2 is the calculated quantity, it is applied directly to the irradiance. These values of irradiance are called UPRLIM and BTMLIM respectively.

In subroutine TARGET, the spatial distribution is assumed to be Gaussian in both the long and short term cases, with axial distance parameters ρ_L and ρ_s, as above. Factors (TL and TS) are computed to give the fraction of total power in the target plane which is reflected by a target (perfectly reflecting) of diameter TD, for the given distribution, with the pattern centered on axis. These reflected powers are then calculated for the incident powers corresponding to irradiances AXINT, UPRLIM and BTMLIM, giving three values called LTAP (long term average power), UPL and BTL for the long term case, and MOST, UPS and BTS for the short term case. In the long term case, these represent the expected range of power intercepted by the target.

In the short term case, the expected wander of the beam has to be taken into account. This is done by treating ρ_c, the measure of beam centroid wander, as the average instantaneous, off-axis position of the beam center. Applying this to the calculated on-axis values, and assuming a small target, gives a factor of $\exp[-(\rho_c/\rho_s)^2]$ to be applied to MOST and BTS to give the average and lower expected powers, STAP and BTSC. The upper power is not reduced, in order to

include the values of power corresponding to little wander in the distribution. The reflectivity is applied to all the final powers to give reflected power values. (These are named with an R in the program; e.g., BTS, when reflectivity is considered, becomes BTSR.)

A logical sorting depending upon the times characteristic of the wander, the scintillation and the pulsed beam is then performed to determine the proper values of expected power to select. Fig. 12 shows the options. AP is the average reflected power, BP is the lower variance point power and UP is the upper variance point power. In most cases of interest, the wander and scintillation times both fall between the pulse duration and the pulse repetition time. The powers used are then LTARP, UPSR and whichever is lower between BTSCR and BTLR.

The three selected values of power are sent to subroutine RTNPTH. There, they are used in three calls to subroutine TURB (after transmittance losses are applied). Each of these calls to TURB returns an average value of axial irradiance. These are referred to as ARPP, URPP and BRPP. The differences (VRPP--ARPP) and (ARPP--BRPP) are evaluated and the larger of the two is taken as a variance measure, from which a log-variance measure VW is calculated using Eq (35).

This log-variance VW is associated with both beam wander and scintillations. When wander is not important, it need not be considered. Therefore, throughout the wander

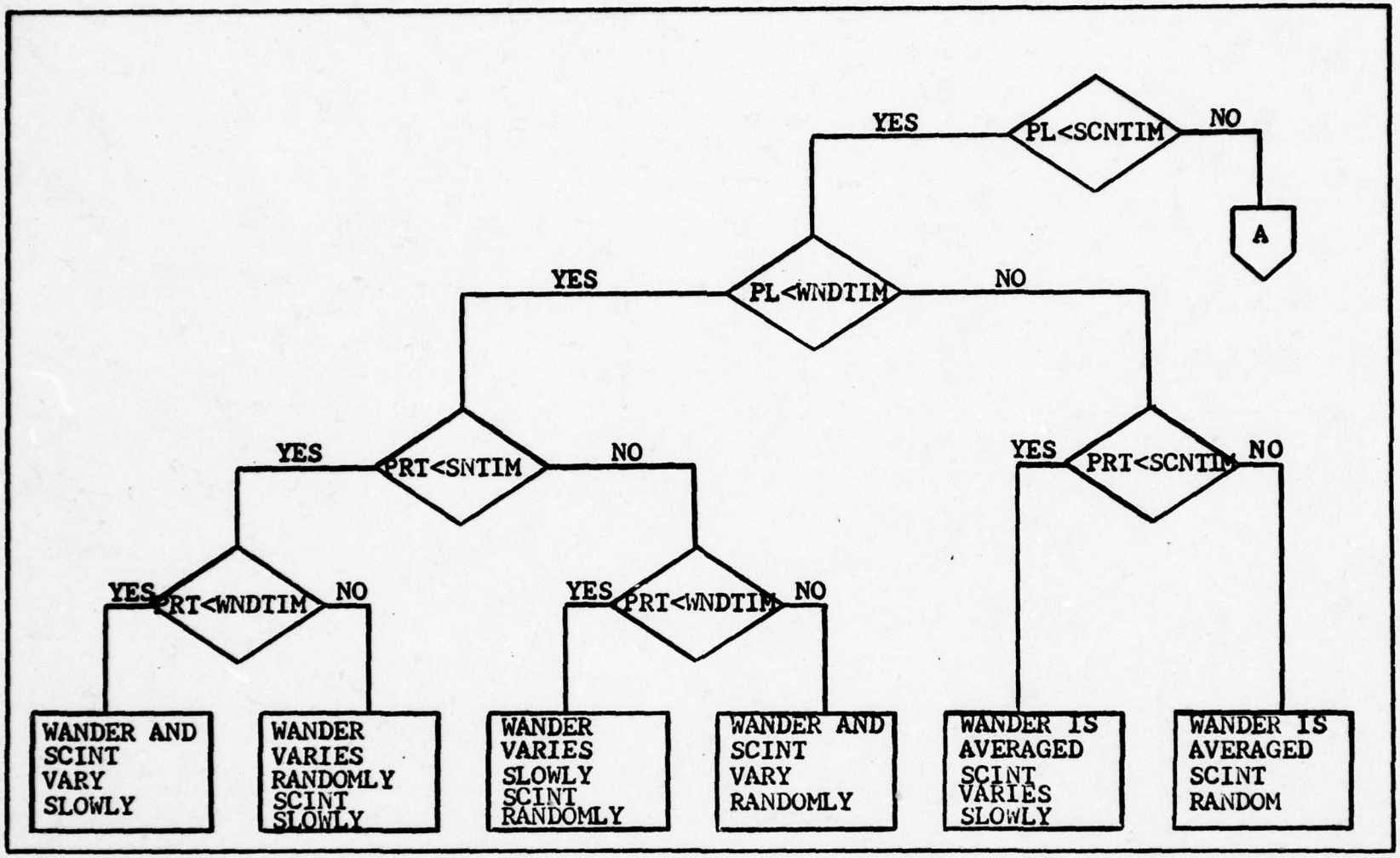


Fig. 12. Relationship of Characteristic Times

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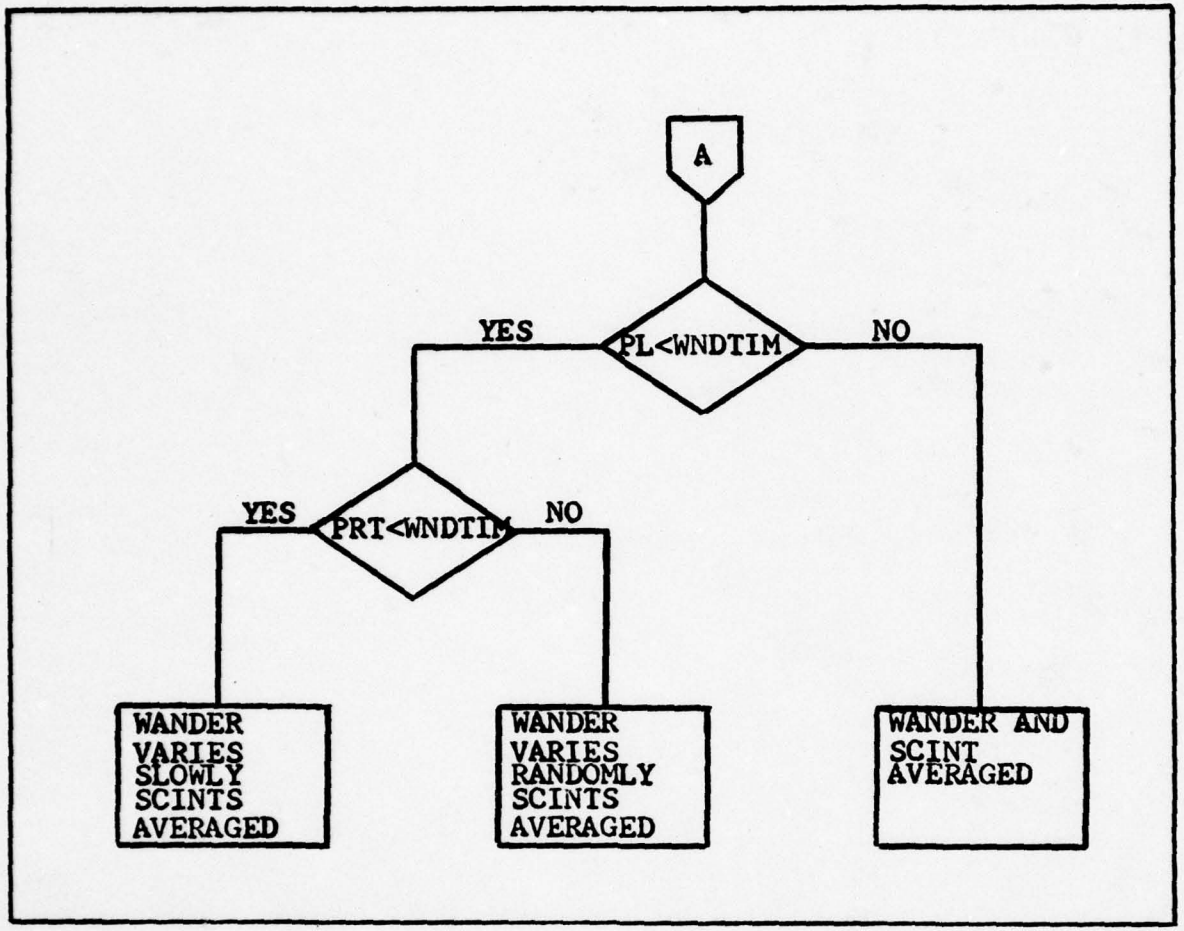


Fig. 12. (continued)

calculations, whenever the wander is found to be insignificant, either because it is time averaged or because the magnitude is small, an index JERKY is set equal to zero. When JERKY is zero in the probability distribution calculations, VW is not used. If JERKY is not equal to zero, the larger of VW and the log-variance from the scintillation calculation is used.

The log-variance due to scintillations alone is calculated for the receiver location simply by adding the variances from both paths. The variance used for the return path is the one calculated in TURB along with the average irradiance. The justification for simply adding these log-variances lies in the Rytov approach of treating the log-irradiance as the dependent random function. Since reflection by the small highly reflective target results in essentially starting over on the propagation problem, the two paths are treated as independent sequential random processes and hence the variances should be additive. The independence of the two paths is reasonable, since the beams, both being divergent, are not comparable in size anywhere except near halfway between the transmitter and target. Therefore, the turbulent effects are different. This would be more rigorously correct if C_N^2 were handled as a function of position, but the approach should give reasonable values of the log-variance at the receiver.

Note that the distributions are calculated and plotted for the irradiance on axis at the receiver. Beam wander

effects are not included for the return path and beam receiver interaction. After RTNPTH is complete, TARGET is called again, using the average irradiance and the highest and lowest expected power in the presence of wander (calculated by TURB, along with URPP and BRPP, by the same method as UPRLIM and BTMLIM). If beam wander is significant (JERKY not equal to zero), a statement is printed out including the average output, the high and low expected output. These high and low values correspond to well out on the wings of the distribution, since they are away from the average value by one variance on the forward path, and then another (different) variance on the reflected path. Hence, the probability that a value would fall outside this range should be less than 10%, but not negligible. If wander is negligible (JERKY equals zero), only the average value of the output is printed, and a direct ratio between the axial irradiances and the powers can be assumed.

No units are specified with the output printout. This is because the receiver sensitivity is used in the place of the reflectivity. The units of the answer for output depend upon the sensitivity value used. The default value is one, so that the output is in watts of optical power on the receiver.

VI. Combined Model

The various atmospheric effects are combined in a program called PULSE. This program handles data input and parts of the written output. All of the calculations of the various parameters are performed in subroutines. The major subroutines are described below.

Input

The inputs required for the program are on formatted cards. All of the input parameters have default values and input cards change these values. The various cards and their required entries are below. The formats required are listed after the card description. The name of the card starts in column one and is not followed by any punctuation. Notice that all numerical fields start in columns 10, 20, 30, etc. The given formats start in column 10.

NUMBER	requires an integer 1, 2 or 3 in column 10. FORMAT (I1)
BEAM	sets the values of wavelength (microns), diameter (meters), divergence (radians), peak power (watts), pulse duration (seconds) and pulse repetition time (seconds). These are the beam parameters for beam number 3. Beams 1 and 2 remain set at default values of the 1.06 and .53 micron beams. FORMAT (7(E 7.1, 3x))

RANGE	transmitter to target (kilometers). FORMAT (F 10.3)
TARGET	target diameter (meters), reflectivity, divergence of the beam after reflection (radians). FORMAT (3(E 7.1, 3x))
TURB	effective refractive-index structure constant (CNSQ) ($m^{-\frac{2}{3}}$), transverse wind velocity (m/sec). FORMAT (E 7.1, 3x, F 10.3)
SETTING	requires one of the following words beginning in column 10. URBAN, RURAL, MARITIME or NONSTAND. If NONSTAND is entered, curve fitting parameters C and D are required in columns 30 and 40. FORMAT (A8, 11x, 2F 10.4)
WEATHER	temperature (^{o}C), atmospheric pressure (mbar), visibility (km), dew point (^{o}C). FORMAT (4(E 7.1, 3x))
RECEIVER	receiver diameter (meters), receiver sensitivity (appropriate units). FORMAT (2(E 7.1, 3x))
NOPLOT	no numerical entry required. This suppresses the plots of irradiance probability distribution.
PRINT	no numerical entry required. This prints output of intermediate results and comments. Primarily useful if problems are encountered in the program.
ENDPROB	no numerical entry required. This tells the program that no more input cards are to be read.

The default values set in the program are equivalent to an input deck of:

```
NUMBER      2
RANGE       8.0
TARGET      0.025       1.0         0.003
TURB        5.0 E-15    2.0
SETTING     URBAN
WEATHER     25.0        975.0       15.0        22.0
RECEIVER    0.0762      1.0
ENDPROB
```

If no ENDPROB is included, the end-of-file will perform the same function. The NUMBER card sets the number of beams to be considered. As currently set up, only beam 3 can be varied. This is done in order to be able to set the values for the variable beam, while using the fixed values for the other two beams. It is not easy to investigate the results of changing beam parameters. A few minor changes to the program, as listed in Appendix E, allow the inclusion of a NUMBER card, followed by the appropriate number of BEAM cards (up to 3), to change all the beam parameters, rather than just beam 3.

Subroutines

The major subroutines are listed below, with a summary of what each one does. The basis of each calculation is discussed in the appropriate chapter.

AFCRL — sets the value of molecular absorption coefficient (KAPPAM) equal to .001 and

flags wavelengths where absorption may require better calculations.

AROSOL — calculates the aerosol extinction coefficient (SIGMA) based upon approximations to the various aerosol models.

RAYLEE — calculates the molecular scattering coefficient (SIGMAM) based upon Rayleigh scattering. The main program then sums the three coefficients to give the total extinction coefficient (SIGMA). This is used to get transmittance.

TURB — calculates the basic irradiance scintillation parameters by use of various formulas and function subroutines. It also calculates characteristic scintillation time, SCNTIM.

AXIAL — calculates the average irradiance and the beam wander parameters, including the characteristic wander time, WNDTIM.

TARGET — determines the amount of power reflected by the target, based upon initial power, beam parameters, transmittance, target size, reflectivity and the turbulence characteristics. Both characteristic times are involved in determining the pulse-to-pulse behavior of reflected power. It is used again to determine output of the receiver.

RTNPTH — calculates the total power reaching the receiver plane and the irradiance distribution. It calls TURB to evaluate the effects of turbulence. It then calls PROB or PROBZ.

PROB — calculates and plots (if required) the irradiance probability distribution at the receiver based upon the two-parameter log-normal distribution.

PROB2 — calculates and plots (if required) the irradiance probability distribution at the receiver based upon the three-parameter truncated log-normal distribution.

Output

The output is basically in two forms, printed and plotted. The printed output (Fig. 13) first repeats the input cards. It lists, for each beam, the beam parameters, turbulence structure parameter and transverse wind speed. It then tells which probability distribution is assumed for the given parameters, followed by the mean, median and upper and lower quartile points of the irradiance distribution. The next statement addresses the effect of beam wander at the target. If the parameter JERKY was set equal to zero in the wander calculations, the phrase "wander is not significant" is printed. If JERKY is not equal to zero, the statement "Distribution is modified by beam wander" is printed. This serves as a warning that there has been a wander factor added to the log-variance and that the form of the distribution is probably not accurate. With divergent beams, it is unlikely that this situation occurs.

The last two statements concern effects at the receiver. The first is a statement derived from the relationships between the characteristic times of the pulsed beam, beam

```
WAVELENGTH DIAMETER   DIVERGENCE    POWER       PD          PRT
 1.060E+00  1.000E-02  3.000E-03  1.100E+07  6.000E-09  3.333E-02
CNSQ =  5.000E-15     V =  2.000E+00

THREE-PARAMETER TRUNCATED LOG-NORMAL DISTRIBUTION IS ASSUMED.
MEAN IRRADIANCE ON AXIS IS  1.976E-04 (W/M**2)
MEDIAN IRRADIANCE ON AXIS IS  8.052E-05 (W/M**2)
ONE HALF OF ALL PULSES WILL BE ABOVE  1.976E-04 OR BELOW  3.281E-05

WANDER IS NOT SIGNIFICANT.

MAGNITUDE OF WANDER IS SMALL COMPARED TO VACUUM BEAM DIVERGENCE.

BOTH WANDER AND SCINTILLATION VARY RANDOMLY PULSE-TO-PULSE.

OUTPUT CORRESPONDING TO THE MEAN IRRADIANCE IS  9.012E-07
```

Fig. 13. Printed Output

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```
WAVELENGTH DIAMETER   DIVERGENCE     POWER        PD           PRT
 5.300E-01  1.000E-02  2.400E-03  7.000E+06  4.000E-09  3.333E-02
CNSQ =  5.000E-15     V =  2.000E+00

THREE-PARAMETER TRUNCATED LOG-NORMAL DISTRIBUTION IS ASSUMED.
MEAN IRRADIANCE ON AXIS IS  2.131E-05 (W/M**2)
MEDIAN IRRADIANCE ON AXIS IS  9.150E-06 (W/M**2)
ONE HALF OF ALL PULSES WILL BE ABOVE  2.137E-05 OR BELOW  3.829E-06

WANDER IS NOT SIGNIFICANT.

MAGNITUDE OF WANDER IS SMALL COMPARED TO VACUUM BEAM DIVERGENCE.

BOTH WANDER AND SCINTILLATION VARY RANDOMLY PULSE-TO-PULSE.

OUTPUT CORRESPONDING TO THE MEAN IRRADIANCE IS  9.717E-08

**********          ORORIGR   //// END  OF LIST ////
```

Fig. 13. (continued)

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wander and scintillation. The effects of wander and scintillation are each described as random, varying slowly or averaged out. If a characteristic time (WNDTIM or SCNTIM) is less than the pulse duration (very unlikely), the effect is averaged out, since each pulse sees some sort of average effect. If a characteristic time is longer than the pulse repetition time, the effect varies slowly, with successive pulses seeing a slightly different situation. If a characteristic time is between the pulse duration and pulse repetition time (the most likely situation), the effect is random, since each pulse sees a changed situation. Although this is calculated for the return path, the parameters are close enough that both paths most likely show the same behavior. The last statement, as described in Chapter V, gives the output from the receiver.

The plotted output (Fig. 14) gives a plot of the assumed probability distribution. The curves are computed by multiplying the probability density at each point by an intensity interval. The intervals are equal in length along the logarithm's axis and centered on each point. Every second point is marked with a symbol. The header gives the type of distribution, log-normal or modified, where modified means the three-parameter distribution. Sigma is the square root of the variance used to calculate the curve. The wavelength and base 10 log of CNSQ are printed to help identify the plot.

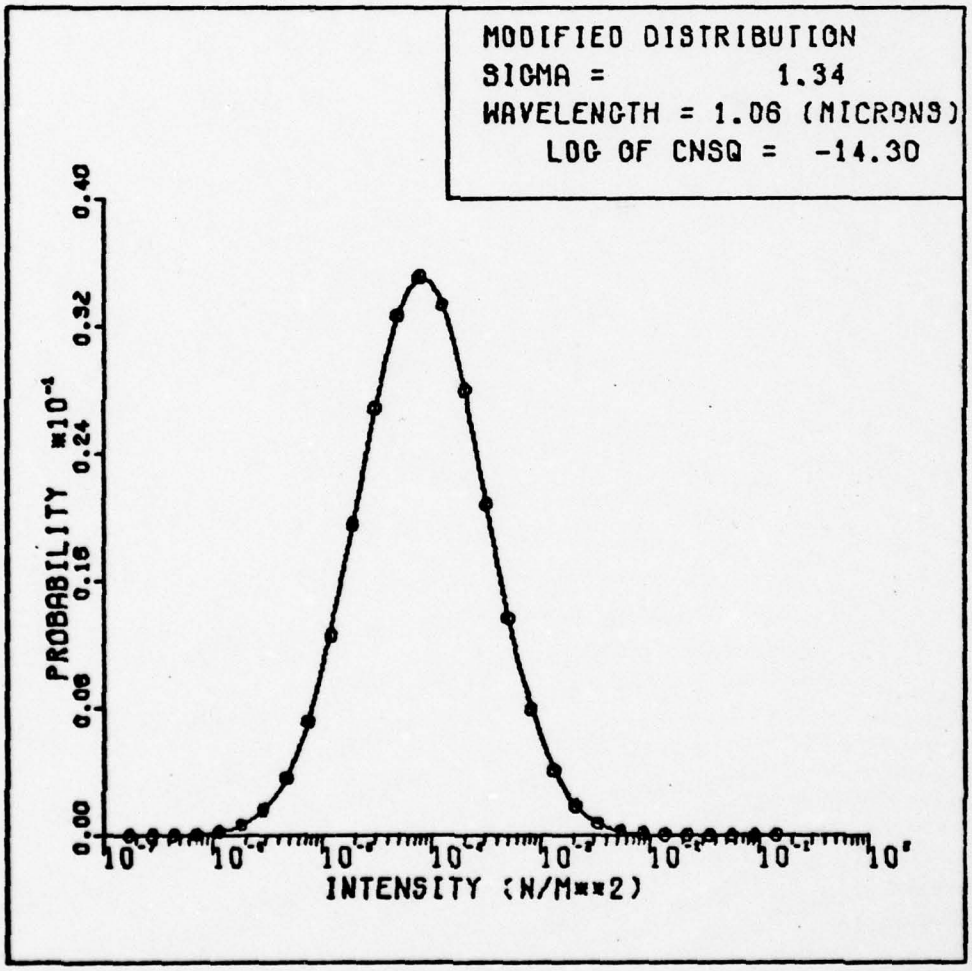


Fig. 14. Plotted Results, Default Values

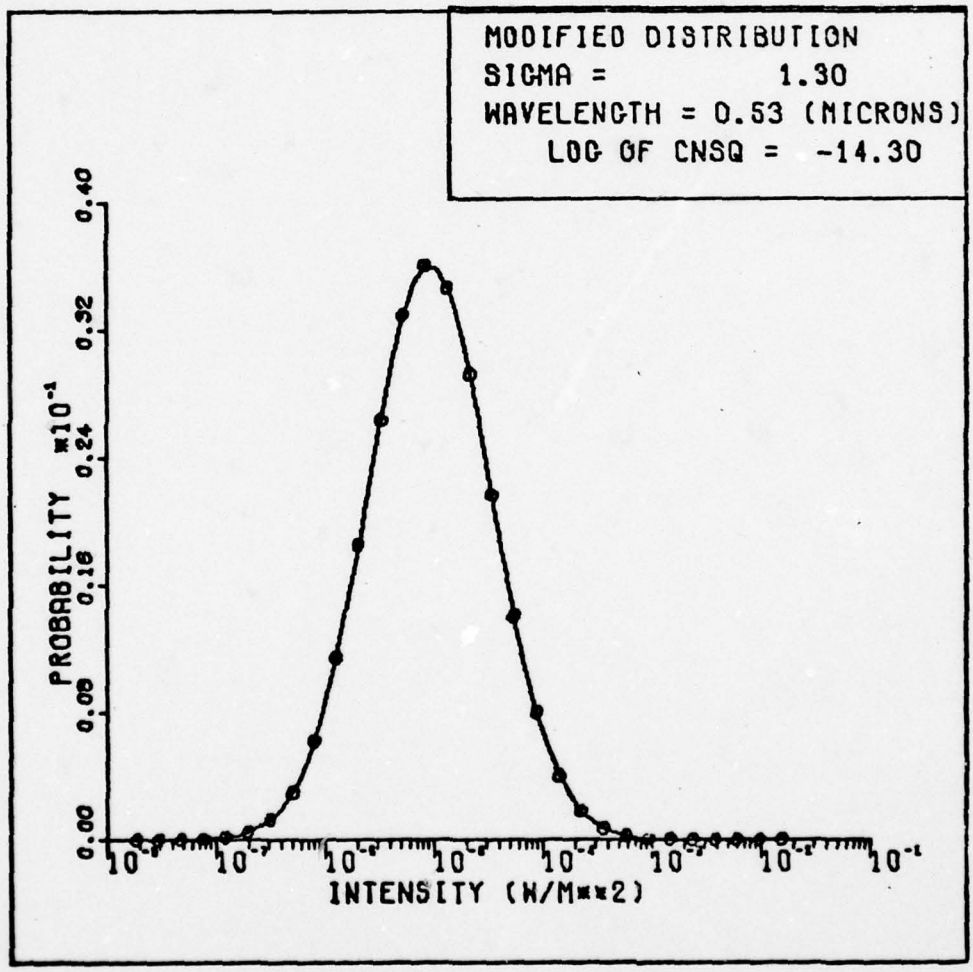


Fig. 14. (continued)

An additional printed output is available. This is a printout of all entries in the program written to TAPE7. An example is given in Appendix B for a single beam problem. The numerical values of selected intermediate results are printed out. Some of these may be of interest in themselves, such as the scattering and absorption coefficients or the vacuum and wander induced beam spread. Others are useful only for checking on problems in the program, such as the number of terms used in the hypergeometric series.

Results

It can be seen from the samples included here, which should correspond to a sunny day with moderate turbulence, that the probable range of irradiance at the receiver varies over several orders of magnitude. Furthermore, the temporal behavior is such that the irradiance varies randomly from pulse-to-pulse. Hence, even in this fixed aim, fixed target situation, it is clear that successive pulses returned from the target may be expected to differ by as much as two orders of magnitude. Indeed, from Fig. 13, it can be seen for the 1.06 micron beam that only half of the pulses fall within a range which goes from 3.28×10^{-5} to 1.97×10^{-4} w/m^2, a factor of 6.0.

Some early results of experimental measurements (Ref 27) are plotted in Fig. 15. The units on the abscissa are essentially power received per pulse, although it is plotted in terms of an effective target cross-section. This rather

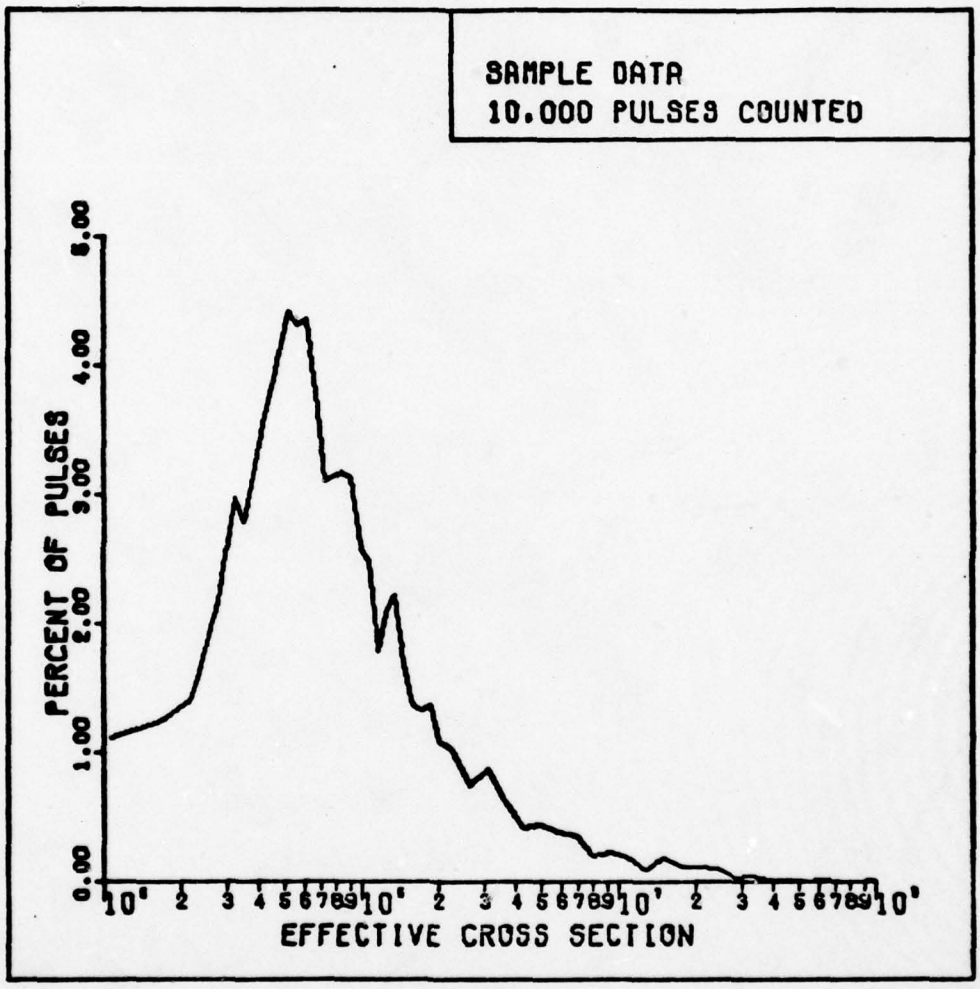


Fig. 15. Typical Experimental Data (1.06 microns)

arbitrary scale avoids the problems of calculation involved in obtaining exact values, and is appropriate for the use on a fixed range, such as is involved here. The ordinate is a linear plot of number of pulses received, plotted as a percentage of total pulses. The plot does not go to lower values of the received power because pulses in that range fall into the noise of the receiver, so that an extremely large number of pulses is counted in a small interval of powers. Virtually all of the left side of the distribution ends up being counted at the level represented by the noise.

From the actual tabulated data, the upper and lower quartile points are found to be about 1.1×10^6 and 3.3×10^5, a factor of 3.3. This corresponds fairly well to the theoretical factor of 6.0, especially since both the theoretical and experimental data are for "typical days," with no attempt to actually match the weather and turbulence conditions.

Several more examples of the theoretical output are included in Appendix B.

VII. Conclusions, Discussion and Recommendations

Conclusions

The model as developed here seems to fit fairly closely the data obtained experimentally, at least at 1.06 microns. The comparison made in Chapter VI was a very rough one, but was sufficient to show a general agreement in form. It is clear that, on days with fairly good visibility so that aerosol losses are not significant, the dominant effect on the received power will be atmospheric turbulence. On a normal sunny day, the power received can be expected to vary randomly on a pulse-to-pulse basis. This variation can easily span two orders of magnitude of received power.

Discussion

A system employing pulsed laser-beams such as these in any sort of tracking or aiming problem must be able to deal with pulse-to-pulse variations of two orders of magnitude even when aiming is exact. Hence, the tracking algorithms must take this into account. Furthermore, it would seem that such a system would be limited to situations where the target is much more reflective than the background, since nearby reflections even two orders of magnitude less might be mistaken for target returns. For a good quality corner reflection, this should present no difficulties in most cases. If the use of less ideal reflection is anticipated,

a study of this problem must be included in the analysis of the tracking problem.

The agreement between the theory and experiment in the .53 micron case is not nearly as good as in the 1.06 micron case (Ref 27). This has only recently been noted, and no effort has been made here to investigate the problem. A starting point would be to agree on units for the power (or irradiance) level and intervals, so that it would be possible to check the actual levels of power received against the theoretical prediction. This is especially important for the .53 micron beam, since the whole distribution is shifted to lower power levels, closer to the system noise level, and it is therefore important to know what part of the distribution is being detected.

Recommendations

Further study needs to be done to explain the .53 micron results, before the model can be used with any degree of assurance as to its accuracy. Furthermore, there needs to be a coordinated effort to compare weather observations (meteorological measurements as well as subjective descriptions of the air mass condition) with values of C_N^2 obtained by fitting the curves to the data. That has not been done here.

If Davidson and Gonzalez-del-Valle (Ref 9), or others, improve the probability distribution description for intermediate and strong turbulence, the distribution functions included here need to be improved as well. In particular,

no special provision has been made here for the case of σ_1^2 greater than 100. For this case, it may be appropriate to include a Rayleigh distribution (Ref 10:81-82). An explicit theoretical form for the parameters of such a distribution has not been derived, however. Current work (Ref 1) is proceeding in many places on understanding these probability distributions, and any systems designer needing accurate values of the expected power fluctuations needs to keep abreast of the current efforts.

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Appendix A

Program Listing

This appendix contains a complete listing of the main program and subroutines. Liberal use has been made of comments throughout. The function of each subroutine has been described in the appropriate chapter.

```
      PROGRAM PULSE(INPUT=/80,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7,     000100
     C PLOT)                                                             000110
C                                                                        000120
C PROGRAM PULSE CALCULATES THE PREDICTED IRRADIANCE DISTRIBUTION      *  000130
C ON AXIS AT THE RECEIVER FOR A PULSED LASER BEAM REFLECTED FROM      *  000140
C A TARGET AND RECEIVED AT THE TRANSMITTER LOCATION.                  *  000150
C                                                                     *  000160
C PROGRAM PULSE IS WRITTEN TO CONTROL THE SUBROUTINES,                *  000170
C WHERE MOST OF THE CALCULATIONS ARE DONE.                            *  000180
C                                                                     *  000190
C INPUT IS BY MEANS OF FORMATTED CARDS.                               *  000200
C MINIMUM REQUIRED INPUT IS A SINGLE ENDPROB CARD. IN THIS            *  000210
C CASE THE DEFAULT VALUES OF ALL PARAMETERS ARE USED FOR BEAMS        *  000220
C ONE AND TWO (1.06 AND .53 MICRONS), AND BEAM THREE IS IGNORED.      *  000230
C                                                                     *  000240
C OTHER POSSIBLE INPUT CARDS:                                         *  000250
C NUMBER   (NUMBER OF BEAMS CALCULATED,  1,2 OR 3 IN COL 10)          *  000260
C BEAM   (WAVELENGTH,DIAMETER,DIVERGENCE,POWER,PD,PRT)                   000270
C RANGE    (RANGE IN KILOMETERS)                                      *  000280
C TARGET     (TARGET DIAMETER,REFLECTANCE,DIVERGENCE)                 *  000290
C TURB     (CNSQ,TRANSVERSE WIND VELOCITY)                            *  000300
C SETTING  (URBAN,RURAL,MARITIME OR NONSTAND)                         *  000310
C WEATHER  (TEMPERATURE,PRESSURE,VISIBILITY,DEWPOINT)                 *  000320
C RECEIVER  (RECEIVER DIAMETER,SENSITIVITY)                           *  000330
C PRINT   (PRINTS INTERMEDIATE RESULTS AND COMMENTS)                  *  000340
C NOPLOT   (SUPPRESSES THE PLOT OF IRRADIANCE DISTRIBUTION)           *  000350
C                                                                     *  000360
C ALL CARDS WHICH REQUIRE NUMERICAL INPUTS ( EXCEPT "NUMBER")         *  000370
C HAVE 10 COLUMN FIELDS STARTING IN COLS 10,20,30,ETC.                *  000380
      DIMENSION KRUD(7),TRANS(3),PD(3),PRT(3)                            000390
      DIMENSION TEMP(7 ),NAMLST(11),SIGMA(3)                             000400
      DIMENSION WVLN(3),DIAM(3),DIVERG(3),POWER(3),WVNM(3)               000410
      DIMENSION JNK(14)                                                  000420
      DIMENSION SIGMAM(3),SIGMAA(3),CLMPWR(3)                            000430
      REAL KAPPAM(3)                                                     000440
```

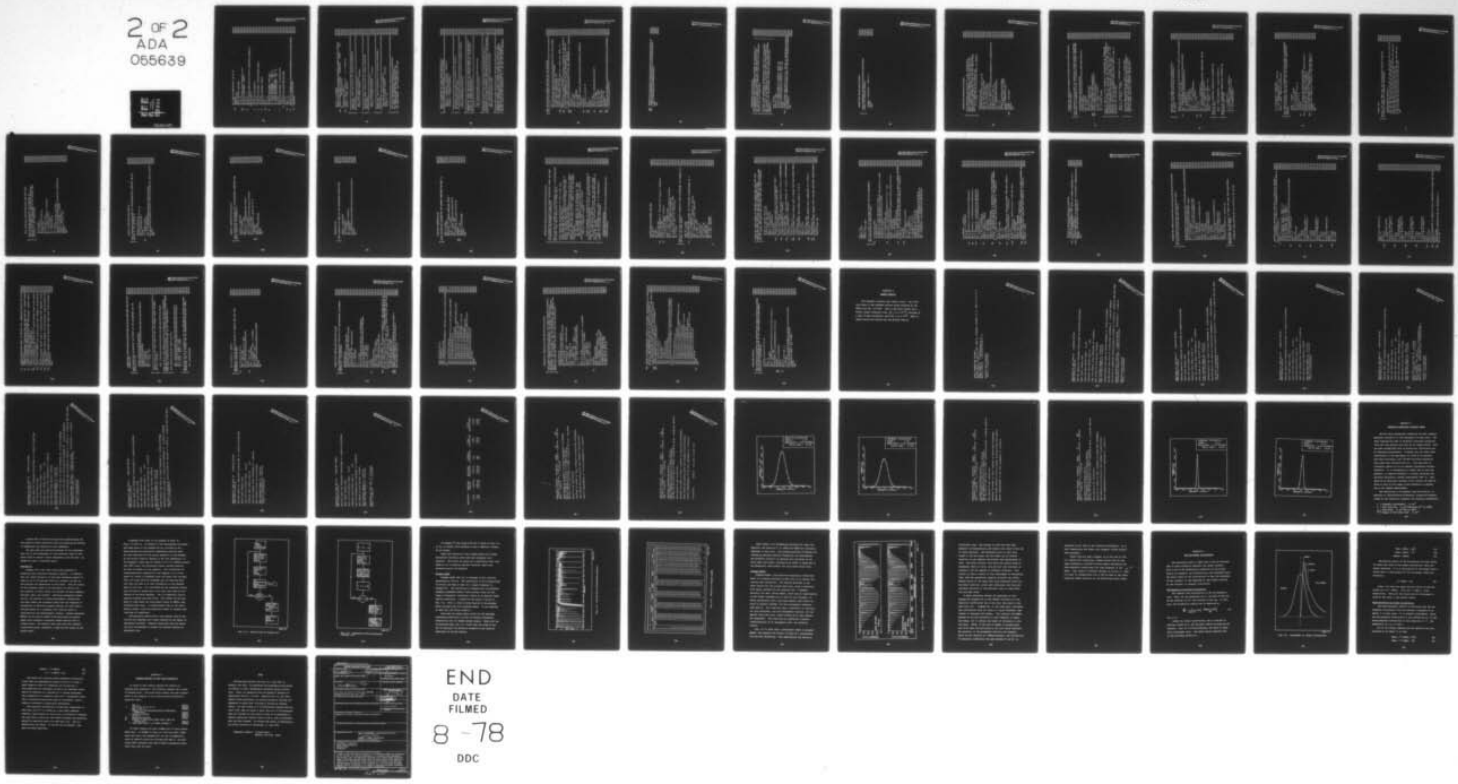

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```
      COMMON/TARGET/ TGTDIA,REFLEC,TGTDIV,V,RHOS,RHOC,RHOL,PI,SCNTIM,WND000450
      COMMON/TRB2/RATIC(25,3)                                          000460
      COMMON/INDEX/M,N,JERKY,NOP,NOPL                                  000470
      COMMON/AIR/GT,GP,GVIS,GOP,C,D,MOD                                000480
      COMMON/RECFEV/RECDIA,SENS                                        000490
      DATA WVLN(1),DIAM(1),DIVERG(1),POWER(1),PD(1),PRT(1)/1.06,       000500
     C.01,.003,1.1E+7,6.0E-9,.03333/                                   000510
      DATA WVLN(2),DIAM(2),DIVERG(2),POWER(2),PD(2),PRT(2)/.53,        000520
     C.01,.0024,7.0E+6,4.0E-9,.03333/                                  000530
      DATA NAMLST/8HNUMBER  ,8HBEAM    ,8HRANGE   ,8HTARGET  ,         000540
     C8HTURB    ,8HSETTING ,8HWEATHER ,8HRECEIVER,8HENDPROB ,8HPRINT   ,000550
     C8HNOPLOT  /                                                      000560
      DATA CNSO,V,NUMBER,PI,MOD/5.0E-15,2.0,2,3.14159,2/               000570
      DATA  P/8.0/                                                     000580
      DATA GT,GP,GVIS,GOP/25.0,975.0,15.0,22.0/                        000590
      DATA RECDIA,SENS/.0762,1.0/                                      000600
      DATA TGTDIA,REFLEC,TGTDIV/0.025,1.0,.003/                        000510
101   FORMAT(A8,1X,7A10)                                               000620
102   FORMAT(" DATA ENTERED IS NOT IN ACCORDANCE WITH REQUIRED FORMAT.")000630
103   FORMAT(7(E7.1,3X));                                              000640
105   FORMAT(A8,11X,2F10.4,30X)                                        000650
106   FORMAT(I1,69X)                                                   000660
107   FORMAT(F10.3,60X)                                                000670
108   FORMAT(2(E7.1,3X),50X)                                           000680
109   FORMAT(E7.1,3X,F10.3,50X)                                        000690
110   FORMAT(3(E7.1,3X),40X)                                           000700
      PI = 3.141592654                                                 000710
      REWIND 7                                                         000720
      NOP = 1                                                          000730
      JERKY = 10                                                       000740
      NOPL = 0                                                         000750
21    READ (5,101) KEY,KRUD                                           000760
      IF(EOF(5)) 77,78                                                 000770
78    PRINT*,KEY,KRUD                                                 000780
      DO 15 MM = 1,11                                                  000790
```


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AD-A055 639 AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OHIO SCH--ETC F/G 20/5
LASER TEST RANGE PROPAGATION MODEL.(U)
DEC 77 W H MACINNIS
UNCLASSIFIED AFIT-GEP/PH/77-6 NL

2 OF 2
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```
      IF ( KEY.EQ.NAMLST(MM)) GO TO 22                                  000800
15    CONTINUE                                                          000810
      PRINT(6,102)                                                      000820
      PRINT (6,101) KEY,KRUD                                            000830
      GO TO 21                                                          000840
22    GO TO (1,2,3,4,5,6,7,8,9,10,11),MM                                000850
1     DECODE(70,106,KRUD)  NUMBER                                       000860
      GO TO 21                                                          000870
2     NUMBER = 3                                                        000880
      DECODE(70,103,KRUD) WVLN(3),DIAM(3),DIVERG(3),POWER(3),           000890
     CPD(3),PRT(3)                                                      000900
      GO TO 21                                                          000910
3     DECODE (70,107,KRUD) R                                            000920
      GO TO 21                                                          000930
4     DECODE(70,110,KRUD) TGTDIA,REFLEC,TGTDIV                          000940
      GO TO 21                                                          000950
5     DECODE(70,109,KRUD) CNSQ,V                                        000960
      GO TO 21                                                          000970
10    NOP=0                                                             000980
      GO TO 21                                                          000990
6     DECODE(70,105,KRUD) MODEL,C,D                                     001000
      IF (MODEL.EQ.8HRURAL   ) MOD= 1                                   001010
      IF (MODEL.EQ.8HURBAN   ) MOD = 2                                  001020
      IF (MODEL.EQ.8HMARITIME)  MOD = 3                                 001030
      IF (MODEL.EQ.8HNONSTAND)  MOD = 4                                 001040
      GO TO 21                                                          001050
7     DECODE(70,103,KRUD) GT,GP,GVIS,GOP                                001060
      GO TO 21                                                          001070
   8   DECODE(70,108,KRUD)RECDIA,SENS                                   001080
      GO TO 21                                                          001090
11    NOPL = 1                                                          001100
      GO TO 21                                                          001110
9     PRINT(7,*) NUMBER,WVLN,DIAM,DIVERG,POWER,R,TGTDIA,REFLEC,MODEL,   001120
     CC,D,MOD,GT,GP,GVIS,GOP                                            001130
77    CONTINUE                                                          001140
```


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```
      DO 33 I = 1,NUMBER                                                    001150
      PRINT(6,173) WVLN(I),DIAM(I),DIVERG(I),POWER(I),PD(I),PRT(I)          001160
 173  FORMAT("1WAVELENGTH DIAMETER   DIVERGENCE    POWER       PD"          001170
     C"          PRT"/6(1PE11.3))                                           001180
      PRINT(6,174) CNSQ,V                                                   001190
 174  FORMAT(" CNSQ = ",1PE10.3,"    V = ",1PE10.3)                         001200
      WVNM(I) = 1.0E4 /WVLN(I)                                              001210
C                                                                           001220
C  ***************************************************************************001230
C   SUBROUTINE  AFCRL CALCULATES THE MOLECULAR ABSORPTION                   001240
C   COEFFICIENT.                                                            001250
C  ***************************************************************************001260
      CALL AFCRL(WVNM(I),KAPPAM(I))                                         001270
      PRINT(7,*)"AFCRL COMPLETE  ",KAPPAM                                   001280
C                                                                           001290
C  ***************************************************************************001300
C   SUBROUTINE AROSOL CALCULATES THE AROSOL EXTINCTION                      001310
C   COEFFICIENT.                                                            001320
C  ***************************************************************************001330
      CALL AROSOL(WVLN(I),SIGMAA(I))                                        001340
      PRINT(7,*)"AROSOL COMPLETE   ",SIGMAA                                 001350
C                                                                           001360
C  ***************************************************************************001370
C   SUBROUTINE  RAYLEE CALCULATES THE MOLECULAR SCATTERING                  001380
C   COEFFICIENT.                                                            001390
C  ***************************************************************************001400
      CALL RAYLEE (WVNM(I),SIGMAM(I))                                       001410
      PRINT(7,*)"RAYLEE COMPLETE   ",SIGMAM                                 001420
      SIGMA(I) = 0.                                                         001430
C                                                                           001440
C  ***************************************************************************001450
C   THE TOTAL ATTENUATION COEFFICIENT IS CALCULATED                         001460
C   BY ADDING THE INDIVIDUAL COEFFICIENTS.                                  001470
C   THE TRANSMITTANCE IS THEN CALCULATED FOR                                001480
C   THE GIVEN RANGE.  THIS TRANSMITTANCE IS THEN                            001490
```


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```
C   USED TO CALCULATE THE TOTAL POWER REACHING THE                    001500
C   TARGET PLANE,WITH NO TURBULENT SCATTER LOSSES.                    001510
C*****************************************************************001520
      SIGMA(I) = SIGMAM(I) +KAPPAM(I) + SIGMAA(I)                     001530
      TRANS(I) = EXP(-1.0*SIGMA(I)*R)                                 001540
      CLMPWR(I) = POWER(I)*TRANS(I)                                   001550
C                                                                     001560
C  *****************************************************************001570
C   SUBROUTINE TURB IS USED TO CALCULATE THE EFFECTS                  001580
C   OF TURBULENCE ON EACH BEAM.                                       001590
C  *****************************************************************001600
      CALL TURB(WVLN(I),R,CNSQ,DIAM(I),DIVERG(I),CLMPWR(I),UPRLIM,    001610
     1BTMLIM,AXINT,VAR,TGTDIA,1,M)                                    001620
C                                                                     001630
C*****************************************************************001640
C SUBROUTINE TARGET CALCULATES THE POWER RETURNED BY THE REFLECTIVE    001650
C TARGET. IT TAKES INTO ACCOUNT BEAM WANDER CAUSED BY TURBULENCE,     001660
C AS WELL AS TARGET REFLECTIVITY.                                     001670
C*****************************************************************001580
      N = 1                                                           001690
      CALL TARGET(CLMPWR(I),BTMLIM,UPRLIM,AP,BP,UP,                   001700
     C TGTDIA,PD(I),PRT(I),REFLEC)                                    001710
C                                                                     001720
C*****************************************************************001730
C SUBROUTINE RTNPTH USES TRANSMITTANCE AND SUBROUTINE TURB TO         001740
C CALCULATE THE AXIAL IRRADIANCE DISPRIBUTION ON AXIS AT THE RECEIVER. 001750
C*****************************************************************001760
      CALL RTNPTH(WVLN(I),R,TRANS(I),CNSQ,AP,BP,UP,ARPP,              001770
     CBRPP,URPP,AAP,VR,AXINT,VAR)                                     001780
C                                                                     001790
C*****************************************************************001800
C SUBROUTINE TARGET IS CALLED AGAIN TO FIND THE EFFECT OF BEAM        001810
C WANDER ON RECEIVED POWER. RECEIVER SENSITIVITY IS USED INSTEAD      001820
C OF REFLECTIVITY,HENCE GIVING OUTPUT OF THE RECEIVER DIRECTLY.       001830
C DEFAULT VALUE OF THE SENSITIVITY IS 1, SO THAT THE VALUES PRODUCED  001840
```


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```
C ARE THE OPTICAL POWERS INCIDENT ON THE RECEIVER.                              001850
C*******************************************************************************001860
      N = 2                                                                     001870
      CALL TARGET(AAP,BRPP,URPP,ARP,BRP,URP,RECDIA,PD(I),PRT(I),SENS)           001880
      IF(JERKY.NE.0) PRINT(6,801) ARP,BRP,URP                                   001890
      IF(JERKY.EQ.0) PRINT(6,802) ARP                                           001900
      PRINT(7,800) WVLN(I),CNSQ,V                                               001910
  800  FORMAT("-WAVELENGTH OF THIS BEAM IS ",1PE10.3,/" CNSQ = ",                001920
     C1PE10.3,"     V  = ",1PE10.3)                                             001930
  801  FORMAT("0BEAM WANDER CAUSES ADDITIONAL VARIATION IN THE OUTPUT."/         001940
     C" OUTPUT CORRESPONDING TO THE MEAN IRRADIANCE IS ",1PE10.3/               001950
     C" RANGE OF OUTPUT IS FROM ",1PE10.3," TO ",1PE10.3)                       001960
  802  FORMAT("0OUTPUT CORRESPONDING TO THE MEAN IRRADIANCE IS ",1PE10.3)        001970
  33   CONTINUE                                                                  001980
       PRINT(7,201)                                                             001990
       PRINT(7,203)                                                             002000
       DO 25 I=1,NUMBER                                                         002010
       PRINT(7,202)                                                             002020
       PRINT(7,202) WVLN(I),SIGMAM(I),KAPPAM(I),SIGMAA(I),SIGMA(I),             002030
     1 TRANS(I)                                                                 002040
  26   CONTINUE                                                                  002050
       IF(NOP.EQ.0) GO TO 79                                                    002060
  82   STOP                                                                     002070
  79   ENDFILE 7                                                                002080
       REWIND 7                                                                 002090
       PRINT(6,85)                                                              002100
  85   FORMAT("1TAPE7 INFORMATION FOLLOWS.")                                    002110
       DO 81 I=1,1000                                                           002120
       IF(EOF(7)) 82,83                                                         002130
  83   READ(7,84) JNK                                                           002140
  84   FORMAT(13A10,A7)                                                         002150
       PRINT(6,84) JNK                                                          002160
  81   CONTINUE                                                                 002170
  201  FORMAT(11H1WAVELENGTH,3X,9HMOLECULAR,4X,9HMOLECULAR,6X,7HAEROSOL,        002180
     1 8X,5HTOTAL,10X,5HTOTAL)                                                  002190
```


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```
202  FORMAT(F10.3,4X,3(G10.3,3X),F10.5,5X,F11.5,5X,E9.3,2(4X,E9.3))      002200
203  FORMAT(15X,7HSCATTER,5X,10HABSORPTION,3X,11HATTENUATION,3X,          002210
     1 11HATTENUATION,3X,13HTRANSMITTANCE)                               002220
      STOP                                                               002230
      END                                                                002240
```


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```
      SUBROUTINE AFCRL(W,KAPPAM)                                          002250
C THIS SUBROUTINE SETS THE MOLECULAR ABSORPTION COEFFICIENT TO        *   002260
C AN APPROXIMATE VALUE CONSISTENT WITH THOSE CALCULATED FROM          *   002270
C THE AIR FORCE GEOPHYSICAL LABORATORY COMPILATION OF ATMOSPHERIC     *   002280
C ABSORPTION LINE PARAMETERS.                                         *   002290
C                                                                     *   002300
C IT FLAGS THOSE WAVELENGTH REGIONS WHERE MORE EXACT CALCULATIONS      *   002310
C MUST BE MADE. THE CABABILITY TO PERFORM THESE CALCULATIONS IS        *   002320
C NOT INCLUDED IN THE SUBROUTINE BECAUSE THEY ARE LONG AND BECAUSE    *   002330
C OPERATION IN THE FLAGGED AREAS IS NEITHER ANTICIPATED NOR           *   002340
C ADVISABLE.                                                          *   002350
C                                                                     *   002360
      REAL KAPPAM                                                         002370
      KAPPAM = .001                                                       002380
      IF(W.GT.10120.0.AND.W.LT.11200.0) PRINT 101                         002390
      IF(W.GT.11870.0.AND.W.LT.12080.0) PRINT 101                         002400
      IF(W.GT.12970.0.AND.W.LT.13170.0) PRINT 101                         002410
      RETURN                                                              002420
  101 FORMAT("0THIS WAVELENGTH FALLS IN A REGION OF SIGNIFICANT MOLECULA  002430
     CR ABSORPTION. DETAILED CALCULATIONS OF MOLECULAR ABSORPTION SHOULD   002440
     C BE MADE.")                                                         002450
      END                                                                 002460
```


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```
      SUBROUTINE RAYLEE(WVNM,SIGMAM)                                    002470
C                                                                       002480
C     THIS SUBROUTINE CALCULATES MOLECULAR SCATTERING                   002490
C     USING THE RAYLEIGH FORMULA.                                       002500
C                                                                       002510
      SIGMAM = (9.87E-20) * WVNM **4                                    002520
      RETURN                                                            002530
      END                                                               002540
```


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```
      SUBROUTINE AROSOL(WVLN,SIGMAA)                                    002550
C                                                                       002560
C   THIS SUBROUTINE CALCULATES THE TOTAL ATTENUATION                    002570
C   DUE TO ATMOSPHERIC AEROSOLS, USING A CHOICE OF THE                  002580
C   THREE AEROSOL MODELS PROPOSED BY SHETTLE AND FENN,                  002590
C   RURAL,URBAN, AND MARITIME. THESE ARE THE MODELS WHICH               002600
C   HAVE BEEN INCORPORATED INTO LOWTRAN 3B.                             002610
C        IF NO MODEL IS SPECIFIED,URBAN MODEL IS ASSUMED.               002620
C                                                                       002630
      DIMENSION A(4),B(4)                                               002640
      COMMON/AIR/GT,GP,GVIS,GDP,C,D,MOD                                 002650
      DATA A/ .077,.088,.141,999./                                      002660
      DATA B/1.21,.98,.196,0./                                          002670
      F(X,Y,Z) = X*Y**(-1.0*Z)                                          002680
      AA(T) = 273.15/(273.15+T)                                         002690
      WATDEN(T) = AA(T) * EXP(18.9766-14.9595*AA(T)-2.4388*AA(T)**2)    002700
      IF(GVIS.GT.23.) MOD =1                                            002710
      IF(GVIS.LE.2.) GO TO 205                                          002720
      GRH = WATDEN(GDP)/WATDEN(GT)                                      002730
      A(4) = C                                                          002740
      B(4) = D                                                          002750
      SIGMAA= F(A(MOD),WVLN,B(MOD))                                     002760
      C = 6.9894E4/ GVIS - 2.0889E2                                     002770
      SIGMAA= SIGMAA*C/2.83E3                                           002780
      RETURN                                                            002790
205   SIGMAA = 3.91/GVIS                                                002800
      RETURN                                                            002810
      END                                                               002820
```


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```
      SUBROUTINE TURB(WVLN,R,CNSQ,DIAM,DIVERG,CLMINT,UPRLIM,BTMLIM,     002830
     C AXINT,VAR,EFD,N)                                                 002840
C                                                                       002850
C THIS SUBROUTINE CALCULATES THE IRRADIANCE SCINTILLATION PARAMETERS    002860
C AND CALLS FOR SUBROUTINE AXIAL TO CALCULATE BEAM WANDER PARAMETERS.   002870
C                                                                       002880
      COMMON/INDEX/M,NN,JERKY,NOP,NOPL                                  002890
      COMMON/TARGET/ TGTDIA,REFLEC,TGTDIV,V,RHOS,RHOC,RHOL,PI,          002900
     C SCNTIM,WNDTIM                                                    002910
      REAL KK,LAMBDA                                                    002920
      REAL LOGVAR                                                       002930
      IF(N.EQ.1) PRINT(7,203)                                           002940
      IF(N.EQ.2) PRINT(7,204)                                           002950
  203 FORMAT("0INCIDENT BEAM BEHAVIOR:")                                002960
  204 FORMAT("0REFLECTED BEAM BEHAVIOR:")                               002970
      F= -1.0*DIAM/(2.0*DIVERG)                                         002980
      LAMBDA = WVLN * 1.0E-6                                            002990
      RR = R * 1.0E3                                                    003000
      KK = 2.0*PI/ LAMBDA                                               003010
C                                                                       003020
C  SIGM1 IS USED AS A TEST PARAMETER IN COMPARISONS OF TURBULENCE       003030
C  STRENGTH. FOR SIGM1 .LT. .3 OR .GT. 25, THE LOG-NORMAL PROBABILITY   003040
C  DISTRIBUTION IS ASSUMED. FOR SIGM1 .GT..3 AND .LT. 25 ,A THREE-      003050
C  PARAMETER LOG-NORMAL DISTRIBUTION IS USED. FOR SIGM1 .LT. 1.8,       003060
C  ISHIMARU'S FORMULA FOR A GAUSSIAN BEAM WAVE IS USED.                 003070
C  FOR SIGM1 .GE. 1.8,AN EMPIRICAL FORMULA FROM FANTE IS USED TO        003080
C  CALCULATE THE LOG-VARIANCE.                                          003081
C                                                                       003090
      SIGM1 = 1.23*KK**(7.0/6.0) * CNSQ*RR**(11.0/6.0)                  003100
      PRINT(7,*)" SIGM1 = ",SIGM1                                       003110
C                                                                       003120
C    NOW APERTURE AVERAGING THE TARGET IS CONSIDERED,                   003130
C    SINCE THE EFFECT OF TURBULENCE ON RECEIVED INTENSITY               003140
C    SCINTILLATIONS IS GREATLY REDUCED WHEN THE TARGET                  003150
C    SIZE IS LARGER THAN THE TRANSVERSE CORRELATION                     003160
```


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```
C     DISTANCE. THE FORMULA USED IS AN APPROXIMATION                          003170
C     TO A PLANE WAVE SOLUTION GIVEN GRAPHICALLY                              003180
C     BY FANTE.                                                               003190
C                                                                             003200
      APAV=.09 +.91*EXP(-1.0*(EFD/(LAMBDA*RR)**.5/.89)**1.5*(1.0+SIGM1))     003210
      IF(SIGM1.GE.1.8)  GO TO 20                                              003220
 10   CALL AXIAL(LAMBDA,DIAM,DIVERG,CLMINT,CNSQ,AXINT,RR,N)                   003230
      VAR  = LOGVAR(CNSQ,LAMBDA,RR,DIAM,0.0)                                  003240
      AA = ALOG(AXINT )                                                       003250
      BB = SQRT(VAR*APAV)                                                     003260
      BTMLIM   = EXP(AA-BB)                                                   003270
      UPRLIM   = EXP ( AA+BB)                                                 003280
      SPCWD  = V / SQRT(LAMBDA*RR)                                            003290
      SCNTIM   = 1.0/SPCWD                                                    003300
 22   IF(N.EQ.2) M=1                                                          003310
      GO TO 24                                                                003320
 20   VAR  = 1.0 + .99/SIGM1**.4                                              003330
      CALL AXIAL(LAMBDA,DIAM,DIVERG,CLMINT ,CNSQ,AXINT ,RR,N)                 003340
      CC = SQRT(VAR*APAV*AXINT**2)                                            003350
      BTMLIM   = AXINT  - CC                                                  003360
      IF(BTMLIM.LT.0.0) BTMLIM = 0.0                                          003370
      UPRLIM   = AXINT  + CC                                                  003380
C                                                                             003390
C  RHOP IS THE TRANSVERSE CORRELATION DISTANCE FOR                            003400
C  A PLANE WAVE.                                                              003410
C                                                                             003420
      RHOP = SQRT(LAMBDA*RR) * 0.36/ SIGM1**.6                                003430
C                                                                             003440
C  RHOD IS THE TRANSVERSE CORRELATION DISTANCE FOR                            003450
C  A GAUSSIAN BEAM WAVE.                                                      003460
C                                                                             003470
      A = (1.0-RR/F)**2                                                       003480
      B = 4.0*RR**2 / (KK**2 * DIAM**4)                                       003490
      C = 1.0 + (DIAM/RHOP)**2 / 3.0                                          003500
      D = (13.0*RR)/(3.0*F)                                                   003510
```


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```
      E = (11.0/3.0) * (RR/F)**2                                        003520
      F = 4.0*RR**2 / (3.0*KK**2 * DIAM**4)                             003530
      G = 1.0 +(DIAM/RHOP)**2 / 4.0                                     003540
      RHOD  = RHOP* (A+B*C)/(1.0-D+E+F*G)                               003550
C                                                                       003560
C THE CHARACTERISTIC TIME FOR IRRADIANCE SCINTILLATIONS IS DETERMINED   003570
C FROM THE TRANSVERSE WIND VELOCITY AND THE TRANSVERSE CORRELATION      003580
C DISTANCE.                                                             003590
C                                                                       003600
      SPDWD  = V/RHOD                                                   003610
      SCNTIM  = 1.0 / SPDWD                                             003620
      VAR = ALOG(1.0+VAR)                                               003630
      IF(SIGM1.GE.25.0) GO TO 22                                        003640
      IF(N.EQ.2) M = 2                                                  003650
 24   CONTINUE                                                          003660
      IF(N.EQ.1.OR.N.EQ.2)PRINT(7,201)SCNTIM                            003670
 201  FORMAT("0CHARACTERISTIC TIME SCALE OF SCINTILLATION ",            003680
     C"PHENOMENA IS  ",1PE10.3," SECONDS.")                             003690
      IF(N.EQ.1.OR.N.EQ.2)PRINT(7,202)APAV                              003700
 202  FORMAT("0THE EFFECT OF IRRADIANCE SCINTILLATIONS IS ",            003710
     1"REDUCED BY A FACTOR OF ",1PE10.3," FOR THIS BEAM.")              003720
      RETURN                                                            003730
      END                                                               003740
```


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```
      BLOCK DATA                                                        003750
C                                                                       003760
C THIS IS THE DATA ARRAY FOR THE INTERPOLATION ROUTINE INVOLVED         003770
C IN CERTAIN RANGES OF TURBULENCE PARAMETERS.                           003780
C                                                                       003790
      COMMON/TRB2/RATIO(26,3)                                           003800
      DATA RATIO/1.0,.77,.8,.86,.89,.91,.92,.93,.94,.95,.96,.97,.97,.97,003810
     1.97,.97,.97,.975,.98,.98,.98,.98,.98,.99,.99,.99,                 003820
     21.0,.71,.68,.66,.71,.72,.75,.78,.81,.84,.85,.87,.88,.89,.90,.91,  003830
     3.92,.93,.935,.94,.945,.95,.955,.96,.965,.97,                      003840
     4 1.0,.71,.67,.61,.52,.65,.70,.74,.77,.80,.82,.835,.85,.86,.87,    003850
     5 .88,.89,.896,.90,.905,.91,.915,.92,.925,.93,.93/                 003860
      END                                                               003870
```


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```
      REAL FUNCTION LOGVAR(CNSQ,WVLN,RNG,DIAM,RHO)                      003880
C                                                                       003890
C  THIS FUNCTION CALCULATES THE VARIANCE IN                             003900
C  THE LOG IRRADIANCE FOR A BEAM WITH AN EFFECTIVE                      003910
C  INITIAL SPOT SIZE DETERMINED BY THE INITIAL BEAM                     003920
C  DIAMETER AT THE TRANSMITTER.                                         003930
C                                                                       003940
      PI=3.14159                                                        003950
      WO = DIAM/2.0                                                     003960
      ALFA1= WVLN/(PI*WO**2)                                            003970
      Z=ALFA1*RNG                                                       003980
      B1 =Z/(1.0 +Z**2)                                                 003990
      B2= 2.0*RHO**2/(WO**2*(1.0+Z**2))                                 004000
      R1 = RNG**(11.0/6.0)                                              004010
      W = 2.0*PI/WVLN                                                   004020
      W2 = W**(7.0/6.0)                                                 004030
      G1 = G(Z)                                                         004040
      G2 = CUMMER(-5.0/6.0,1.0,B2)                                      004050
      LOGVAR=(-8.7)*CNSQ*W2*R1*B1**(5.0/6.0)*(.375*G2-G1)               004060
      PRINT(7,*)"LOGVAR = ",LOGVAR                                      004070
      LOGVAR = ABS(LOGVAR )                                             004080
      PRINT(7,*) "G1 = ",G1                                             004090
      RETURN                                                            004100
      END                                                               004110
```


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```
      COMPLEX FUNCTION HYP(A,B,C,Z)                                          004120
C                                                                            004130
C THIS SUBROUTINE CALCULATES THE HYPERGEOMETRIC FUNCTION FOR ALL             004140
C VALUES OF THE ARGUMENT Z.                                                  004150
C                                                                            004160
      COMPLEX HYP1,Z,Y,X                                                     004170
      IF(CABS(Z).GT.1.0) GO TO 10                                            004180
      HYP = HYP1(A,B,C,Z)                                                    004190
      RETURN                                                                 004200
 10   X = CLOG(-1.0/Z)                                                      004210
      Y = CEXP(5.0/6.0*X)                                                    004220
      HYP = -0.141*(26.942*Y*HYP1(-5.0/6.0,-5.0/3.0,                         004230
     C-5.0/6.0,1.0/Z)-0.833*(-1.0/Z)* HYP1(1.0,1.0/6.0,17.0/6.0,1.0/Z))      004240
      RETURN                                                                 004250
      END                                                                    004260
```


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```
      COMPLEX FUNCTION HYP1(A,B,C,Z)                                    004270
C                                                                       004280
C THIS SUBROUTINE CALCULATES THE HYPERGEOMETRIC FUNCTION FOR            004290
C SMALL VALUES OF THE ARGUMENT Z.                                       004300
C                                                                       004310
      COMPLEX Z,TERM,SUM                                                004320
      TERM = A*B*Z/C                                                    004330
      SUM = 1.0 + TERM                                                  004340
      PRINT(7,*) " HYPERGEOMETRIC TERMS."                               004350
       DO 15 I = 1,100                                                  004360
      TERM = TERM*(A+I)*(B+I)*Z/((I+1.)*(C+I))                          004370
      SUM = SUM + TERM                                                  004380
      IF(CABS(TERM).LE.1.0E-5) GO TO 17                                 004390
 15    CONTINUE                                                         004400
 17   HYP1 = SUM                                                        004410
      PRINT(7,*)I,TERM,SUM                                              004420
      RETURN                                                            004430
      END                                                               004440
```


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```
      FUNCTION G(X)                                                      004450
C                                                                        004460
C THIS FUNCTION IS USED IN THE LOGVARIANCE CALCULATION.                  004470
C                                                                        004480
      COMPLEX  Z,Z1,Z2,Z3                                                004490
      Z=(0.0,1.0)*X                                                      004500
      Z1= (1.0+Z)/Z                                                      004510
      Z2 = (5.0/6.0)* CLOG(Z1)                                           004520
      Z3= CEXP(Z2)                                                       004530
      G = REAL((6.0/11.0)*Z3*HYP(-5.0/6.0,1.0,17.0/6.0,Z))               004540
      RETURN                                                             004550
      END                                                                004560
```


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```
      FUNCTION CUMMER(A,B,Z)                                          004570
C                                                                     004580
C THIS SUBROUTINE CALCULATES THE KUMMER FUNCTION FOR REAL Z.          004590
C                                                                     004600
      TERM = A*Z/B                                                    004610
      SUM =1.0+ TERM                                                  004620
      PRINT(7,*) "  KUMMER FUNCTION TERMS "                           004630
      DO 18  I = 1,100                                                004640
      TERM = TERM * (A+I)*Z/((I+1)*(B+I))                             004650
      SUM = SUM + TERM                                                004660
      IF(ABS(TERM).LE.1.0E-7) GO TO 19                                004670
 18   CONTINUE                                                        004680
 19   CUMMER = SUM                                                    004690
      PRINT(7,*)I,TERM,SUM                                            004700
      RETURN                                                          004710
      END                                                             004720
```


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```
      SUBROUTINE AXIAL(WVL,DIA,DIV,PWR,CSQ,AXNT,RR,N)                    004730
C                                                                        004740
C THIS SUBROUTINE CALCULATES BEAM SPREAD PARAMETERS, WHICH ARE USED      004750
C TO CALCULATE BEAM-TARGET INTERACTION.                                  004760
C                                                                        004770
C SCALE LENGTHS OF TURBULENCE ARE ARBITRARILY SET AT 1 MILLIMETER FOR    004780
C THE INNER SCALE AND 50 METERS FOR THE OUTER SCALE.                     004790
C                                                                        004800
C  WEAK TURBULENCE IS CHARACTERIZED BY BOTH A LONG TERM                  004810
C  AND A SHORT TERM BEAM SPREAD.                                         004820
C  LARGE (COMPARED TO BEAM DIAMETER) TURBULENT EDDIES TEND TO            004830
C  DEFLECT THE BEAM. SMALL EDDIES TEND TO BROADEN THE BEAM               004840
C  WITHOUT SIGNIFICANT DEFLECTION.                                       004850
C      THE DEFLECTION VARIES IN DIRECTION DUE TO FLOW OF EDDIES          004860
C  ACROSS THE BEAM. THE TIME INTERVALS CHARACTERISTIC OF THIS            004870
C  VARIATION ARE OF THE ORDER OF D/V  WHERE V IS THE TRANSVERSE          004880
C  FLOW VELOCITY.                                                        004890
C     THE MEAN SQUARE RADIUS DUE TO BROADENING IS  RHOS.                 004900
C     THE MEAN SQUARE RADIUS DUE TO DEFLECTION IS  RHOC.                 004910
C     OVER TIMES LONG COMPARED TO DELT (=D/V), A SPOT OF                 004920
C  MEAN SQUARE RADIUS  RHOL  IS OBSERVED, WHERE:                         004930
C       RHOL**2 = RHOS**2 + RHOC**2                                      004940
C                                                                        004950
C     STRONG TURBULENCE IS CHARACTERIZED BY THE BEAM BREAKING UP         004960
C  INTO MULTIPLE BEAMS.(ACCORDING TO FANTE PULSES OVER 100 PS            004970
C  BEHAVE THE SAME AS CW SIGNALS)                                        004980
C     IN THE WORK BELOW, RHOL  AND RHOS  ARE THE RADII WHERE             004990
C  THE AVERAGE OF LONG AND SHORT TERM IRRADIANCE ARE REDUCED TO          005000
C  EXP(-1) OF MAXIMUM.                                                   005010
C     RHOL IS CALCULATED FIRST, SINCE IT IS APPROXIMATELY                005020
C  CORRECT FOR ALL CASES CONSIDERED.                                     005030
C                                                                        005040
      COMMON/TRB2/RATIO(26,3)                                            005050
      COMMON/TARGET/TGTDIA,REFLEC,TGTDIV,V,RHOS,RHOC,RHOL,PI,            005060
     C SCNTIM,WNDTIM                                                     005070
```


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```
      COMMON/INDEX/M,NN,JERKY,NOP,NOPL                                  005080
      REAL LO,LI                                                        005090
      LI=.001                                                           005100
      LO= 50.0                                                          005110
      PRINT(7,11) WVL                                                   005120
 11   FORMAT("1WAVELENGTH OF THIS BEAM IS ",E11.4," METERS.")           005130
      PRINT(7,12) CSQ                                                   005140
 12   FORMAT(" CNSQ EQUALS ",1PE8.2)                                    005150
      F = -1*DIA/(2.0*DIV)                                              005160
      WVVCT = 2.0 * 3.14159 / WVL                                       005170
      RHOO = (.626* (WVVCT)**2* RR *CSQ)**(-3.0/5.0)                    005180
      D1 = 4.0 * RR**2/ (WVVCT**2 *RHOO**2)                             005190
      D2 = 2.2 * RR**3 *LI**(-1.0/3.0) * CSQ                            005200
      XO=(WVVCT)**2 *CSQ * LI **(5.0/3.0)                               005210
      XO = 1.0/XO                                                       005220
C                                                                       005230
C XOR IS A CRITICAL DISTANCE PARAMETER WHICH DETERMINES THE FORMULA TO  005240
C BE USED FOR BEAM SPREAD.                                              005250
C                                                                       005260
      XOR= XO *1.0E-3                                                   005270
      PRINT(7,13) XOR                                                   005280
 13   FORMAT("0CRITICAL RANGE FOR TURBULENCE CALCULATIONS IS ",         005290
     C1PE9.3," KILOMETERS.")                                            005300
      VBS1= 4.0 * RR**2 / (WVVCT**2 * DIA**2)                           005310
      VBS2 = DIA**2/4.0 *(1.0 - RR/F)**2                                005320
      VBS = VBS1 + VBS2                                                 005330
      XXX = VBS + D1                                                    005340
      XX =SQRT(XXX)                                                     005350
      D11=SQRT(D1)                                                      005360
      YYY = VBS + D2                                                    005370
      YY= SQRT(YYY)                                                     005380
      D22=SQRT(D2)                                                      005390
      AVS = PWR / (PI*XXX)                                              005400
      AVL = PWR / (PI*YYY)                                              005410
C                                                                       005420
```


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```
C THERE ARE THREE RANGES OF INTEREST: RANGE MUCH LESS THAN XOR,          005430
C RANGE MUCH MORE THAN XOR, AND THE INTERMEDIATE RANGE.                  005440
C THE VALUE OF  RHOL IN THE INTERMEDIATE RANGE IS TAKEN AS THE MEAN      005450
C OF THE VALUES CALCULATED FROM THE SHORT AND LONG RANGE FORMULAS.       005460
C                                                                        005470
      IF(RR.LE.(.1*XO)) GO TO 15                                         005480
      IF(RR.GE.(10* XO)) GO TO 25                                        005490
      AXNT = (AVS + AVL)/2.0                                             005500
      RHOLSQ = (XXX+YYY)/2.0                                             005510
      RHOL = SQRT(RHOLSQ)                                                005520
      PRINT(7,401)                                                       005530
 401  FORMAT("0THE GIVEN RANGE IS IN THE INTERMEDIATE AREA."             005540
     C," THE TWO VALUES CALCULATED FOR RHOL ARE: ")                      005550
      PRINT(7,402) XX,AVS                                                005560
 402  FORMAT(" RHOL USING SHORT RANGE FORMULA IS ",F10.3," CORRESPONDING005570
     C AXIAL IRRADIANCE IS ",1PE10.3)                                    005580
      PRINT(7,403)YY,AVL                                                 005590
 403  FORMAT(" RHOL USING  LONG RANGE FORMULA IS ",F10.3," CORRESPONDING005600
     C AXIAL IRRADIANCE IS ",1PE10.3)                                    005610
      GO TO 26                                                           005620
 15   PRINT(7,404) XX                                                    005630
 404  FORMAT("0SHORT RANGE FORMULA USED."/"0LONG TERM BEAM SPREAD EQUALS005640
     " ",F8.3)                                                           005650
      PRINT(7,405) D11                                                   005660
 405  FORMAT("0TURBULENT BEAM SPREAD ALONE IS ",F8.3)                    005670
      AXNT = AVS                                                         005680
      RHOLSQ = XXX                                                       005690
      RHOL = XX                                                          005700
      PRINT(7,406) AXNT                                                  005710
 406  FORMAT("0LONG TERM AVERAGE AXIAL IRRADIANCE IS ",1PE10.3)          005720
      GO TO 26                                                           005730
 25   PRINT(7,407) YY                                                    005740
 407  FORMAT("0LONG RANGE FORMULA USED."/"0LONG TERM BEAM SPREAD EQUALS  005750
     C", F8.3)                                                           005760
      PRINT(7,405) D22                                                   005770
```


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```
      AXNT = AVL                                                        005780
      RHOLSQ = YYY                                                      005790
      RHOL = YY                                                         005800
      PRINT(7,406) AXNT                                                 005810
C                                                                       005820
C  THE FOUR CASES OF BEAM WANDER RANGES ARE NOW CONSIDERED              005830
C  FOR CALCULATION OF RHOS AND RHOC.                                    005840
C                                                                       005850
 26   T=AMIN1(DIA,RHOO)                                                 005860
      Q= WVVCT*T**2                                                     005870
      IF(RHOO.LE.(.1*DIA).AND.RR.LE.Q) LOC = 1                          005880
      IF(RHOO.GT.(.1*DIA).AND.RHOO.LT.(2.5*DIA).AND.RR.LE.Q) LOC=2      005890
      IF(RHOO.GT.(2.5*DIA).AND.RR.LE.Q) LOC=3                           005900
      IF(RR.GT.Q) LOC=4                                                 005910
      GO TO (70,80,90,100) LOC                                          005920
 70   RHOSQ = VBS + 4.0*(RR/WVVCT/RHOO)**2 *(1.0 - .62*                 005930
     C(RHOO/DIA)**(1.0/3.0))**1.2                                       005940
      RHOCSQ = 2.97*RR**2/(WVVCT**2*RHOO**(5.0/3.0)*DIA**(1./3.))       005950
      RHOS = SQRT(RHOSQ)                                                005960
      RHOC = SQRT(RHOCSQ)                                               005970
      PRINT(7,71) RHOS,RHOC,RHOL                                        005980
 71   FORMAT(" SHORT TERM BEAM SPREAD RADIUS IS ",1PE10.3/"0BEAM CENTROI005990
     CD WANDER IS ",1PE10.3/"LONG TERM BEAM SPREAD IS ",1PE10.3)        006000
      GO TO 110                                                         006010
 80   X=RHOO/DIA                                                        006020
      B1 = WVVCT*DIA**2/(4.0*RR)                                        006030
      B2 = 1.0 - RR/F                                                   006040
      BETASQ = (B1*B2)**2                                               006050
      I = INT(10.0*X + 1.0)                                             006060
      A = 10.0*X + 1.0 - I                                              006070
      IF(BETASQ.LE..1) GO TO 81                                         006080
      IF(BETASQ.GE.10.) GO TO 82                                        006090
      IF(BETASQ.GT..1.AND.BETASQ.LE.1.0) GO TO 83                       006100
      ALO = RATIO(I,2) + A* (RATIO(I+1,2)-RATIO(I,2))                   006110
      AHI = RATIO(I,1) + A*(RATIO(I+1,1)-RATIO(I,1))                    006120
```


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```
      B =(BETASQ - 1.0)/9.0                                              006130
      AMU = ALO + B*(AHI-ALO)                                            006140
      GO TO 85                                                           006150
81    AMU = RATIO(I,3)+ A*(RATIO(I+1,3)-RATIO(I,3))                      006160
      GO TO 85                                                           006170
82    AMU = RATIO(I,1) + A*(RATIO(I+1,1)-RATIO(I,1))                     006180
      GO TO 85                                                           006190
83    ALO = RATIO(I,3) + A*(RATIO(I+1,3)-RATIO(I,3))                     006200
      AHI = RATIO(I,2) + A*(RATIO(I+1,2)-RATIO(I,2))                     006210
      B = (BETASQ-0.1)/.9                                                006220
      AMU = ALO + B*(AHI-ALO)                                            006230
85    RHOSQ = AMU**2 * RHOL**2                                           006240
      RHOCSQ = RHOL**2 - RHOSQ                                           006250
      RHOS = SQRT(RHOSQ)                                                 006260
      RHOC = SQRT(RHOCSQ)                                                006270
      PRINT(7,86) RHOS,RHOC,RHOL                                         006280
86    FORMAT(" COHERENCE DISTANCE IS COMPARABLE TO BEAM DIAMETER."/       006290
     C" SHORT TERM BEAM SPREAD IS  ",1PE10.3,/" BEAM CENTROID WANDER     006300
     C IS  ",1PE10.3/" LONG TERM BEAM SPREAD IS  ",1PE10.3)              006310
      GO TO 110                                                          006320
90    PRINT(7,91) RHOL                                                   006330
      RHOC = 0.0                                                         006340
      JERKY = 0                                                          006350
      RHOS = RHOL                                                        006360
91    FORMAT(" BEAM WANDER IS NEGLIGIBLE.SHORT TERM BEAM SPREAD =        006370
     C LONG TERM BEAM SPREAD  =  ",1PE10.3)                              006380
      GO TO 110                                                          006390
100   RHOCSQ = CSQ**1.6 * WVVCT**(1./15.) * RR**(37./15.)                006400
      RHOC = SQRT(RHOCSQ)                                                006410
      RHOS = SQRT(VBS)                                                   006420
      PRINT(7,101) RHOC,RHOL                                             006430
      IF(RHOL.GT.(1.5*RHOS)) PRINT(6,112)                                006440
101   FORMAT("0BEAM BREAKS UP INTO MULTIPLE PATCHES."/"0BEAM CENTROID WA006450
     CNDER IS ",1PE10.3,/" LONG TERM BEAM SPREAD IS ",1PE10.3)           006460
110   WNDTIM = DIA/V                                                     006470
```


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```
      IF(N.EQ.1.OR.N.EQ.2)PRINT(7,111)WNDTIM                          006480
      IF(RHOC.LT.(.05*RHOL)) JERKY = 0                                006490
111   FORMAT("0CHARACTERISTIC TIME SCALE OF WANDER PHENOMENA IS ",    006500
     C1PE10.3," SECONDS.")                                            006510
112   FORMAT("0BEAM BREAKUP IS SIGNIFICANT. NO ACCURATE DESCRIPTION OF P006520
     CROBABLE DISTRIBUTION IS AVAILABLE.")                            006530
      RETURN                                                          006540
      END                                                             006550
```


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```
      SUBROUTINE TARGET(CLMPWR,BTMLIM,UPRLIM,AP,BP,UP,TD,PL,PRT,RFL)     006560
C                                                                        006570
C THIS SUBROUTINE CALCULATES THE BEAM WANDER EFFECT                      006580
C AT THE TARGET AND THE REFLECTED POWER.                                 006590
C                                                                        006600
C                                                                        006610
C                                                                        006620
      COMMON/TARGET/TGTDIA,REFLEC,TDIV,V,RHOS,RHOC,RHOL,PI,SCNTIM,WNDTIM006630
      COMMON/INDEX/M,NN,JERKY,NOP,NOPL                                   006640
      REAL LTARP,LTAP,LEAST,LEASTR,MOST,MOSTR                            006650
      PI = 3.141592654                                                   006660
      TL = 1.0 - EXP(-1.0*(TD/(2.0*RHOL))**2)                            006670
      TS = 1.0- EXP(-1.0*(TD/(2.0*RHOS))**2)                             006680
      LTAP = CLMPWR*TL                                                   006690
      MOST = CLMPWR*TS                                                   006700
      STAP = MOST*EXP(-1.0*(RHOC/RHOS)**2)                               006710
      LTARP = LTAP*RFL                                                   006720
      MOSTR= MOST*RFL                                                    006730
      STARP = STAP*RFL                                                   006740
      BTS = BTMLIM*PI*RHOL**2*TS                                         006750
      BTL = BTMLIM*PI*RHOL**2*TL                                         006760
      BTSR = BTS*RFL                                                     006770
      BTLR = BTL*RFL                                                     006780
      BTSC = BTS * EXP(-1.0*(RHOC/RHOS)**2)                              006790
      BTSCR = BTSC*RFL                                                   006800
      UPS = UPRLIM*PI*RHOL**2*TS                                         006810
      UPL = UPRLIM*PI*RHOL**2*TL                                         006820
      UPSR = UPS*RFL                                                     006830
      UPLR = UPL*RFL                                                     006840
      IF(NN.EQ.1) PRINT(7,1) TD,RFL,TDIV                                 006850
C                                                                        006860
C BEAM WANDER IS NEGLIGIBLE IF SHORT AND LONG TERM GEOMETRICAL           006870
C FACTORS ARE NEARLY EQUAL.                                              006880
C                                                                        006890
      IF(NN.EQ.2.AND.(ABS(TS-TL).LT.(.01*TL))) GO TO 200                 006900
```


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```
1     FORMAT("0TARGET PARAMETERS: DIAMETER = ",1PE10.3," METERS",          006910
     ""     REFLECTIVITY = ",1PE10.3,/," DIVERGENCE OF REFLECTED BEAM =",006920
     C1PE10.3," MILLIRAD.")                                               006930
   9  INDEX = 1                                                           006940
      IF(PL.LT.SCNTIM) INDEX = INDEX + 8                                  006950
      IF(PL.LT.WNDTIM) INDEX = INDEX + 4                                  006960
      IF(PRT.LT.SCNTIM) INDEX = INDEX+2                                   006970
      IF(PRT.LT.WNDTIM) INDEX = INDEX + 1                                 006980
      GO TO (10,2,2,2,50,60,2,2,90,2,110,2,130,140,150,160)INDEX          006990
10    IF(NN.EQ.2) PRINT(5,11)                                             007000
      JERKY = 0                                                           007010
      NOPL = 1                                                            007020
      AP=BP=UP=LTARP                                                      007030
      RETURN                                                              007040
50    AP=LTAPP                                                            007050
      BP = STARP                                                          007060
      UP = MOSTR                                                          007070
      IF(JERKY.NE.0) JERKY = 1                                            007080
      IF(NN.EQ.2)PRINT(6,51)                                              007090
      RETURN                                                              007100
60    AP = LTARP                                                          007110
      BP = STAPP                                                          007120
      UP = MOSTR                                                          007130
      IF(JERKY.NE.0) JERKY = 1                                            007140
      IF(NN.EQ.2)PRINT(6,61)                                              007150
      RETURN                                                              007160
90    AP= LTAPP                                                           007170
      BP = BTLR                                                           007180
      UP = UPLR                                                           007190
      IF(NN.EQ.2) PRINT(5,91)                                             007200
      JERKY = 0                                                           007210
      RETURN                                                              007220
110   AP = LTARP                                                          007230
      BP = BTLR                                                           007240
      UP = UPLR                                                           007250
```


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```
      IF(NN.EQ.2) PRINT(6,111)                                          007260
      JERKY = 0                                                         007270
      RETURN                                                            007280
130   AP = LTARP                                                        007290
      BP = AMIN1(BTLR,BTSCR)                                            007300
      UP = UPSR                                                         007310
      IF(NN.EQ.2) PRINT(6,131)                                          007320
      IF(JERKY.NE.0) JERKY = 1                                          007330
      RETURN                                                            007340
140   AP=LTARP                                                          007350
      UP = UPSR                                                         007360
      BP = AMIN1(BTSCR,BTLR)                                            007370
      IF(NN.EQ.2) PRINT(6,141)                                          007380
      IF(JERKY.NE.0) JERKY = 1                                          007390
      RETURN                                                            007400
150   AP = LTARP                                                        007410
      UP = UPSR                                                         007420
      BP = BTSCR                                                        007430
      IF(NN.EQ.2) PRINT(6,151)                                          007440
      IF(JERKY.NE.0) JERKY = 1                                          007450
      RETURN                                                            007460
160   AP = LTARP                                                        007470
      BP = BTSR                                                         007480
      UP = UPSR                                                         007490
      IF(NN.EQ.2) PRINT(6,161)                                          007500
      IF(JERKY.NE.0) JERKY = 1                                          007510
      RETURN                                                            007520
200   JERKY = 0                                                         007530
      PRINT(6,202)                                                      007540
      GO TO 9                                                           007550
202   FORMAT("0MAGNITUDE OF WANDER IS SMALL COMPARED TO VACUUM BEAM DIVE007560
     "RGENCE.")                                                         007570
2     PRINT(6,195)                                                      007580
195   FORMAT("0TIME PARAMETERS ARE NOT REASONABLE.")                    007590
      GO TO 130                                                         007600
```


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```
11    FORMAT("0RECEIVED POWER IS UNIFORM. ALL TURBULENT EFFECTS ARE AVER007610
     CAGED OUT.")                                                      007620
51    FORMAT("0IRRADIANCE SCINTILLATIONS ARE AVERAGED OUT. WANDER CAUSES007630
     C RANDOM CHANGES IN POWER BETWEEN PULSES.")                       007640
61    FORMAT("0IRRADIANCE SCINTILLATIONS ARE AVERAGEDOUT. WANDER CAUSES 007650
     CORIFT IN POWER BETWEEN PULSES.")                                 007660
91    FORMAT("0WANDER IS AVERAGED OUT.")                                007670
111   FORMAT("0WANDER IS AVERAGED OUT. SCINTILLATIONS CAUSE SLOW VARIATI007680
     CONS PULSE-TO-PULSE.")                                            007690
131   FORMAT("0BOTH WANDER AND SCINTILLATION VARY RANDOMLY PULSE-TO-PULS007700
     CE.")                                                             007710
141   FORMAT("0WANDER VARIES SLOWLY. SCINTILLATIONS VARY RANDOMLY PULSE-007720
     CTO-PULSE.")                                                      007730
151   FORMAT("0WANDER VARIES RANDOMLY PULSE-TO-PULSE. SCINTILLATIONS VAR007740
     CY SLOWLY.")                                                      007750
161   FORMAT("0BOTH WANDER AND SCITILLATIONS CAUSE SLOW PULSE-TO-PULSE V007760
     CARIATION.")                                                      007770
      END                                                              007780
```


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```
      SUBROUTINE RTNPTH(WVLN,R,TRANS,CNSQ,AP,BP,UP,ARPP,BBP,UUP,AAP,VR,  007790
     CAXINT,VAR)                                                        007800
C                                                                       007810
C THIS SUBROUTINE CALCULATES THE EFFECT OF THE ATMOSPHERE ON THE        007820
C REFLECTED BEAM.                                                       007830
C                                                                       007840
      COMMON/INDEX/M,N,JERKY,NOP,NOPL                                   007850
      COMMON/TARGET/TD,RFL,TDIV,V,RHOS,RHOC,RHOL,PI,SCNTIM,WNDTIM       007860
      COMMON/RECFEV/RD,SENS                                             007870
      COMMON/DIST/VW                                                    007880
      AAP = TRANS*AP                                                    007890
      ABP= TRANS * BP                                                   007900
      AUP = TRANS * UP                                                  007910
C                                                                       007920
C  ***************************************************************************007930
C  TURB IS CALLED THE FIRST TIME TO GET THE AVERAGE POWER INCIDENT      007940
C  ON THE RECEIVER.                                                     007950
C                                                                       007960
      CALL TURB(WVLN,R,CNSQ,TD,TDIV,AAP,UAP,BAP,ARPP,VR1,RD,2)          007970
C                                                                       007980
C TURB IS CALLED THE SECOND AND THIRD TIMES GET THE MEAN IRRADIANCE     007990
C ASSUMING THE LOWEST AND HIGHEST (1/E) EXPECTED REFLECTED POWER (BASED 008000
C UPON BEAM WANDER AND SCINTILLATIONS ON THE FORWARD BEAM.)             008010
C                                                                       008020
C  AND MAXIMUM EXPECTED POWER ON AXIS.                                  008030
C                                                                       008040
      CALL TURB(WVLN,R,CNSQ,TD,TDIV,ABP,UBP,BBP,BRPP,VR2,RD,3)          008050
      CALL TURB(WVLN,R,CNSQ,TD,TDIV,AUP,UUP,BUP,URPP,VR3,RD,3)          008060
      UD = (URPP - ARPP) / ARPP                                         008070
      BD = (ARPP - BRPP) / ARPP                                         008080
C                                                                       008090
C VW IS THE LOG OF THE LARGER OF THE TWO DIFFERENCES BETWEEN THE MEAN   008100
C IRRADIANCE AND THE TWOHIGH AND LOW IRRADIANCES CALCULATED ABOVE.      008110
C                                                                       008120
      VW = AMAX1(UD,BD)                                                 008130
```


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```
      VW = ALOG(1.0 + VW*VW)                                          008140
C                                                                     008150
C SUBROUTINE PROB OR PROB2 IS CALLED TO COMPUTE AND PLOT THE          008160
C IRRADIANCE DISTRIBUTION.                                            008170
C                                                                     008180
 10   IF (M.EQ.2) GO TO 11                                            008190
      RVAR = VAR + VR1                                                008200
      RMU = ALOG(ARPP) -0.5 * RVAR                                    008210
      CALL PROB(RMU,RVAR,WVLN,ARPP,CNSQ)                              008220
      RETURN                                                          008230
 11   RVAR = VAR + VR1                                                008240
      TTAU = -1.0E-6*ARPP                                             008250
      RMU = ALOG(ARPP - TTAU) - 0.5*RVAR                              008260
      ALPHA = ARPP - TTAU                                             008270
      CALL PROB2(TTAU,ALPHA,RVAR,RMU,WVLN,CNSQ)                       008280
      RETURN                                                          008290
      END                                                             008300
```


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```
      SUBROUTINE PROB(AO,VAR,WVLN,ARPP,CNSQ)                            008310
C                                                                       008320
C THIS SUBROUTINE CALCULATES AND PLOTS THE TWO-PARAMETER LOG-NORMAL     008330
C PROBABILITY DISTRIBUTION.                                             008340
C                                                                       008350
      COMMON/DIST/VW                                                    008360
      COMMON/INDEX/M,N,JERKY,NOP,NOPL                                   008370
      DIMENSION P(62),AX(62),DAX(62),PRB(62)                            008380
      AX(1) = ARPP/1153.                                                008390
      IF(JERKY.NE.0) VAR = AMAX1(VAR,VW)                                008400
      AMED = EXP(AO)                                                    008410
      SIGMA = SQRT(VAR)                                                 008420
      I=1                                                               008430
      DO 11  K=1,60                                                     008440
      ARG=-1.0*(ALOG(AX(I))-AO)**2 / (2.0*SIGMA**2)                     008450
      P(I)=(1.0/(SQRT(6.28318)*SIGMA*AX(I)))*EXP(ARG)                   008460
      AX(I+1)=1.2649*AX(I)                                              008470
      DAX(I) = .2356* AX(I)                                             008480
      PRB(I)= P(I) * DAX(I)                                             008490
      I = I+1                                                           008500
11    CONTINUE                                                          008510
      ALGN=ALOG10(CNSQ)                                                 008520
      UQRT=EXP(AO + .67*SIGMA)                                          008530
      BQRT= EXP(AO - .67 * SIGMA)                                       008540
      PRINT(6,902)ARPP,AMED,UQRT,BQRT                                   008550
      IF(NOPL.EQ.1) GO TO 12                                            008560
902   FORMAT("0LOG-NORMAL DISTRIBUTION ASSUMED."/" MEAN IRRADIANCE ON AX008570
     CIS IS",1PE10.3," (W/M**2)",        /" MEDIAN IRRADIANCE ON AXIS IS008580
     C",1PE10.3," (W/M**2)"/" ONE HALF OF ALL PULSES WILL BE ABOVE ",1PE008590
     C10.3," OR BELOW ",1PE10.3," (W/M**2)")                            008600
      IF(JERKY.NE.0) PRINT(6,903)                                       008610
      IF(JERKY.EQ.0)PRINT(6,904)                                        008620
903   FORMAT("0DISTRIBUTION IS MODIFIED BY BEAM WANDER.")               008630
904   FORMAT("0BEAM WANDER IS NOT SIGNIFICANT.")                        008640
      CALL PLOT(0.0,-11.0,-3)                                           008650
```


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```
      CALL PLOT(1.0,1.0,-3)                                                    008660
      CALL FACTOR(.7)                                                          008670
      CALL LGSCAL(AX,6.0,60)                                                   008680
      CALL LGAXIS(0.0,0.0,18HINTENSITY (W/M**2),-18,6.0,0.0,AX(61),AX(62008690
     C))                                                                       0087 0
      CALL SCALE(PRB,5.0,60,1)                                                 008 0
      CALL AXIS(0.0,0.0,11HPROBABILITY,11,5.0,90.0,PRB(61),PRB(62))            008720
      CALL LGLINE(AX,PRB,60,2,1,-1)                                            008730
      CALL RECT(-.75,-1.0,7.5,7.5,0.0,3)                                       008740
      CALL SYMBOL(3.0,6.2,.14,22HLOGNORMAL DISTRIBUTION,0.0,22)                008750
      CALL SYMBOL(3.0,5.9,.14,7HSIGMA =,0.0,7)                                 008760
      CALL NUMBER(5.3,5.9,.14,SIGMA,0.0,2)                                     008770
      CALL SYMBOL(3.0,5.6,.14,12HWAVELENGTH =,0.0,12)                          008780
      CALL NUMBER(4.8,5.6,.14,WVLN,0.0,2)                                      008790
      CALL SYMBOL(5.5,5.6,.14,9H(MICRONS),0.0,9)                               008800
      CALL SYMBOL(3.5,5.3,.14,13HLOG OF CNSQ =,0.0,13)                         008810
      CALL NUMBER(5.6,5.3,.14,ALCN,0.0,2)                                      008820
      CALL RECT(2.7,5.0,1.50,4.05,0.0,3)                                       008830
      CALL PLOTE(N)                                                            008840
12    RETURN                                                                   008850
      END                                                                      008860
```


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```
      SUBROUTINE PROB2(TAU,ALPHA,VRPR,AOP,WVLN,CNSQ)                    008870
C                                                                       008880
C THIS SUBROUTINE CALCULATES AND PLOTS THE THREE-PARAMETER TRUNCATED     008890
C LOG-NORMAL PROBABILITY DISTRIBUTION. THE OFFSET PARAMETER IS          008900
C ARBITRARILY SET AT (1.0E-6 * THE MEAN IRRADIANCE). THE TRUNCATION     008910
C POINT IS AT ZERO IRRADIANCE. (DUE TO THE PLOTTING RANGE CHOSEN, THE   008920
C TRUNCATION DOES NOT ENTER EXPLICITLY INTO THE CALCULATION.)           008930
C                                                                       008940
      COMMON/DIST/VW                                                    008950
      COMMON/INDEX/M,N,JERKY,NOP,NOPL                                   008960
      DIMENSION P(62),AX(62),PRB(62),DAX(62)                            008970
      AXO = -1.0*TAU                                                    008980
      IF(JERKY.NE.0) VRPR = AMAX1(VRPR,VW)                              008990
      ARPP = ALPHA - AXO                                                009000
      AMED = EXP(AOP) - AXO                                             009010
      SIGMA = SQRT(VRPR)                                                009020
      AX(1) =(ARPP + AXO) / 1151.                                       009030
      Y = (ALOG(AXO)-AOP) / SQRT(2.0*VRPR)                              009040
      A = 1.0/ (SQRT(6.283185*VRPR)*ERFC(Y))                            009050
      I=1                                                               009060
      DO 11 K = 1,60                                                    009070
      ARG=-1.0*(ALOG(AX(I)+AXO)-AOP)**2 / (2.0*VRPR)                    009080
      P(I) = A/(AX(I)+AXO) * EXP(ARG)                                   009090
      AX(I+1) = 1.2649*AX(I)                                            009100
      DAX(I) = .2356* AX(I)                                             009110
      PRB(I) = P(I) * DAX(I)                                            009120
      I = I+1                                                           009130
11    CONTINUE                                                          009140
      ALCN= ALOG10(CNSQ)                                                009150
      UQRT= EXP(AOP+.67*SIGMA) - AXO                                    009160
      BQRT = EXP(AOP - .67*SIGMA) - AXO                                 009170
      PRINT(6,901)ARPP,AMED,UQRT,BQRT                                   009180
      IF(JERKY.NE.0) PRINT(6,903)                                       009190
      IF(JERKY.EQ.0) PRINT(6,904)                                       009200
      IF(NOPL.EQ.1) GO TO 12                                            009210
```


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```
901  FORMAT("0THREE-PARAMETER TRUNCATED LOG-NORMAL DISTRIBUTION IS ASSU009220
     CMED."/" MEAN IRRADIANCE ON AXIS IS ",1PE10.3," (W/M**2)"/          009230
     C" MEDIAN IRRADIANCE ON AXIS IS ",1PE10.3," (W/M**2)"/" ONE HALF OF009240
     C ALL PULSES WILL BE ABOVE ",1PE10.3," OR BELOW ",1PE10.3)          009250
903  FORMAT("0DISTRIBUTION IS MODIFIED BY BEAM WANDER.")                 009260
904  FORMAT("0WANDER IS NOT SIGNIFICANT.")                               009270
     CALL PLOT(0.0,-11.0,-3)                                             009280
     CALL PLOT(1.0,1.0,-3)                                               009290
     CALL FACTOR(1.0)                                                    009300
     CALL FACTOR(.7)                                                     009310
     CALL LGSCAL(AX,6.0,60)                                              009320
     CALL SCALE(PRB,5.0,60,1)                                            009330
     CALL AXIS(0.0,0.0,11HPROBABILITY,11,5.0,90.0,PRB(61),PRB(62))       009340
     CALL LGAXIS(0.0,0.0,18HINTENSITY (W/M**2),-18,6.0,0.0,AX(61),       009350
    C AX(52))                                                            009360
     CALL LGLINE(AX,PRB,60,2,1,-1)                                       009370
     CALL RECT(-.75,-1.0,7.5,7.5,0.0,3)                                  009380
     CALL SYMBOL(3.0,6.2,.14,21HMODIFIED DISTRIBUTION,0.0,21)            009390
     CALL SYMBOL(3.0,5.9,.14,7HSIGMA =,0.0,7)                            009400
     CALL NUMBER(5.3,5.9,.14,SIGMA,0.0,2)                                009410
     CALL SYMBOL(3.0,5.6,.14,12HWAVELENGTH =,0.0,12)                     009420
     CALL NUMBER(4.8,5.6,.14,WVLN,0.0,2)                                 009430
     CALL SYMBOL(5.5,5.6,.14,9H(MICRONS),0.0,9)                          009440
     CALL SYMBOL(3.5,5.3,.14,13HLOG OF CNSQ =,0.0,13)                    009450
     CALL NUMBER(5.6,5.3,.14,ALCN,0.0,2)                                 009460
     CALL RECT(2.7,5.0,1.5,4.05,0.0,3)                                   009470
     CALL PLOTE(N)                                                       009480
12   RETURN                                                              009490
     END                                                                 009500
```


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```
      FUNCTION ERFC(X)                                                  009510
C                                                                       009520
C THIS FUNCTION CALCULATES THE COMPLEMENTARY ERROR FUNCTION AS NEEDED   009530
C FOR THE NORMALIZATION FACTOR IN THE THREE-PARAMETER LOG-NORMAL        009540
C PROBABILITY DISTRIBUTION.                                             009550
C                                                                       009560
      IF(ABS(X).GT.2.0) GO TO 30                                        009570
      SUM = X                                                           009580
      TERM = X                                                          009590
      DO 10 N=2,1000                                                    009600
      TERM = TERM*(-1.0)*X**2*(2.0*N-3.0)/((2.*N-1.)*(N-1.))            009610
      SUM = SUM + TERM                                                  009620
      IF(ABS(TERM).LE.(.0001*ABS(SUM))) GO TO 20                        009630
 10   CONTINUE                                                          009640
 20   ERFC=1.0-1.12838*SUM                                              009650
      RETURN                                                            009660
 30   NEG = 0                                                           009670
      IF(X.LT.0.0) NEG = 1                                              009680
      X = ABS(X)                                                        009690
      ERFC= EXP(-1.0*X**2)/X/SQRT(3.14159)*(1.0-1.0/(2.*X**2)           009700
     C +3.0/(2.*X**2)**2 -15./(2.*X**2)**3)                             009710
      IF(NEG.EQ.1) ERFC = 2.0 - ERFC                                    009720
      RETURN                                                            009730
      END                                                               009740
```


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Appendix B

Sample Results

This appendix contains more sample output. The first type shown is the expanded printed output obtained by the PRINT card (pp. 121-130). Next is the basic output for a fairly strong turbulence case, $C_N^2 = 1.0 \times 10^{-14}$, followed by a case of weak turbulence, where $C_N^2 = 1.0 \times 10^{-16}$. Both of these include the printed and the plotted results.

```
TAPE7 INFORMATION FOLLOWS.
2 1.06 .53 0. .01 .01 0. .003 .0024 0. 11000000. 7000000. 0. 8. .025 1. 0 0. 0. 2
AFCRL COMPLETE  .001 0. 0.
AROSOL COMPLETE    .1307151079953 0. 0.
RAYLEE COMPLETE    .0007817964456159 0. 0.

INCIDENT BEAM BEHAVIOR:
 SIGM1 = 7.018211128504
```


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WAVELENGTH OF THIS BEAM IS .1060E-05 METERS.
CNSQ EQUALS 5.00E-15

CRITICAL RANGE FOR TURBULENCE CALCULATIONS IS 5.692E+02 KILOMETERS.

SHORT RANGE FORMULA USED.

LONG TERM BEAM SPREAD EQUALS 24.007

TURBULENT BEAM SPREAD ALONE IS .158

LONG TERM AVERAGE AXIAL IRRADIANCE IS 2.105E+03

BEAM BREAKS UP INTO MULTIPLE PATCHES.

BEAM CENTROID WANDER IS 3.970E-07
LONG TERM BEAM SPREAD IS 2.401E+01

CHARACTERISTIC TIME SCALE OF WANDER PHENOMENA IS 5.000E-03 SECONDS.

CHARACTERISTIC TIME SCALE OF SCINTILLATION PHENOMENA IS 1.405E-03 SECONDS.

THE EFFECT OF IRRADIANCE SCINTILLATIONS IS REDUCED BY A FACTOR OF 3.257E-01 FOR THIS BEAM.

TARGET PARAMETERS: DIAMETER = 2.500E-02 METERS REFLECTIVITY = 1.000E+00
DIVERGENCE OF REFLECTED BEAM = 3.000E-03 MILLIRAD.

REFLECTED BEAM BEHAVIOR:
SIGM1 = 7.018211128504

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WAVELENGTH OF THIS BEAM IS .1060E-05 METERS.
CNSQ EQUALS 5.00E-15

CRITICAL RANGE FOR TURBULENCE CALCULATIONS IS 5.692E+02 KILOMETERS.

SHORT RANGE FORMULA USED.

LONG TERM BEAM SPREAD EQUALS 24.013

TURBULENT BEAM SPREAD ALONE IS .158

LONG TERM AVERAGE AXIAL IRRADIANCE IS 1.976E-04

BEAM BREAKS UP INTO MULTIPLE PATCHES.

BEAM CENTROID WANDER IS 3.970E-07
LONG TERM BEAM SPREAD IS 2.401E+01

CHARACTERISTIC TIME SCALE OF WANDER PHENOMENA IS 1.250E-02 SECONDS.

CHARACTERISTIC TIME SCALE OF SCINTILLATION PHENOMENA IS 1.405E-03 SECONDS.

THE EFFECT OF IRRADIANCE SCINTILLATIONS IS REDUCED BY A FACTOR OF 9.069E-02 FOR THIS BEAM.
SIGM1 = 7.018211128504

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WAVELENGTH OF THIS BEAM IS .1060E-05 METERS.
CNSQ EQUALS 5.00E-15

CRITICAL RANGE FOR TURBULENCE CALCULATIONS IS 5.692E+02 KILOMETERS.

SHORT RANGE FORMULA USED.

LONG TERM BEAM SPREAD EQUALS 24.013

TURBULENT BEAM SPREAD ALONE IS .158

LONG TERM AVERAGE AXIAL IRRADIANCE IS 6.161E-05

BEAM BREAKS UP INTO MULTIPLE PATCHES.

BEAM CENTROID WANDER IS 3.970E-07
LONG TERM BEAM SPREAD IS 2.401E+01
SIGM1 = 7.018211128504

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```
WAVELENGTH OF THIS BEAM IS    .1060E-05 METERS.
CNSQ EQUALS 5.00E-15

CRITICAL RANGE FOR TURBULENCE CALCULATIONS IS 5.692E+02 KILOMETERS.

SHORT RANGE FORMULA USED.

LONG TERM BEAM SPREAD EQUALS    24.013

TURBULENT BEAM SPREAD ALONE IS     .158

LONG TERM AVERAGE AXIAL IRRADIANCE IS  3.336E-04

BEAM BREAKS UP INTO MULTIPLE PATCHES.

BEAM CENTROID WANDER IS  3.970E-07
LONG TERM BEAM SPREAD IS  2.401E+01


WAVELENGTH OF THIS BEAM IS  1.060E+00
CNSQ =  5.000E-15     V  =  2.000E+00
AFGRL COMPLETE  .001 .001 0.
AROSOL COMPLETE    .1307151079953 .2578310289526 0.
RAYLEE COMPLETE    .0007817964456159 .01250874312985 0.

INCIDENT BEAM BEHAVIOR:
 SIGM1 = 15.75535127754
```


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WAVELENGTH OF THIS BEAM IS .5300E-06 METERS.
CNSQ EQUALS 5.00E-15

CRITICAL RANGE FOR TURBULENCE CALCULATIONS IS 1.423E+02 KILOMETERS.

SHORT RANGE FORMULA USED.

LONG TERM BEAM SPREAD EQUALS 19.206

TURBULENT BEAM SPREAD ALONE IS .181

LONG TERM AVERAGE AXIAL IRRADIANCE IS 6.892E+02

BEAM BREAKS UP INTO MULTIPLE PATCHES.

BEAM CENTROID WANDER IS 4.062E-07
LONG TERM BEAM SPREAD IS 1.921E+01

CHARACTERISTIC TIME SCALE OF WANDER PHENOMENA IS 5.000E-03 SECONDS.

CHARACTERISTIC TIME SCALE OF SCINTILLATION PHENOMENA IS 6.114E-04 SECONDS.

THE EFFECT OF IRRADIANCE SCINTILLATIONS IS REDUCED BY A FACTOR OF 9.789E-02 FOR THIS BEAM.

TARGET PARAMETERS: DIAMETER = 2.500E-02 METERS REFLECTIVITY = 1.000E+00
DIVERGENCE OF REFLECTED BEAM = 3.000E-03 MILLIRAD.

REFLECTED BEAM BEHAVIOR:
SIGM1 = 15.75535127754

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WAVELENGTH OF THIS BEAM IS .5300E-06 METERS.
CNSQ EQUALS 5.00E-15

CRITICAL RANGE FOR TURBULENCE CALCULATIONS IS 1.423E+02 KILOMETERS.

SHORT RANGE FORMULA USED.

LONG TERM BEAM SPREAD EQUALS 24.013

TURBULENT BEAM SPREAD ALONE IS .181

LONG TERM AVERAGE AXIAL IRRADIANCE IS 2.131E-05

BEAM BREAKS UP INTO MULTIPLE PATCHES.

BEAM CENTROID WANDER IS 4.062E-07
LONG TERM BEAM SPREAD IS 2.401E+01

CHARACTERISTIC TIME SCALE OF WANDER PHENOMENA IS 1.250E-02 SECONDS.

CHARACTERISTIC TIME SCALE OF SCINTILLATION PHENOMENA IS 6.115E-04 SECONDS.

THE EFFECT OF IRRADIANCE SCINTILLATIONS IS REDUCED BY A FACTOR OF 9.000E-02 FOR THIS BEAM.
SIGM1 = 15.7553512775 4

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```
WAVELENGTH OF THIS BEAM IS    .5300E-06 METERS.
CNSQ EQUALS 5.00E-15

CRITICAL RANGE FOR TURBULENCE CALCULATIONS IS 1.423E+02 KILOMETERS.

SHORT RANGE FORMULA USED.

LONG TERM BEAM SPREAD EQUALS   24.013

TURBULENT BEAM SPREAD ALONE IS      .181

LONG TERM AVERAGE AXIAL IRRADIANCE IS  1.362E-05

BEAM BREAKS UP INTO MULTIPLE PATCHES.

BEAM CENTROID WANDER IS  4.062E-07
LONG TERM BEAM SPREAD IS  2.401E+01
 SIGM1 = 15.75535127754
```


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```
WAVELENGTH OF THIS BEAM IS    .5300E-06 METERS.
CNSQ EQUALS 5.00E-15

CRITICAL RANGE FOR TURBULENCE CALCULATIONS IS 1.423E+02 KILOMETERS.

SHORT RANGE FORMULA USED.

LONG TERM BEAM SPREAD EQUALS   24.013

TURBULENT BEAM SPREAD ALONE IS      .181

LONG TERM AVERAGE AXIAL IRRADIANCE IS  2.899E-05

BEAM BREAKS UP INTO MULTIPLE PATCHES.

BEAM CENTROID WANDER IS  4.062E-07
LONG TERM BEAM SPREAD IS  2.401E+01


WAVELENGTH OF THIS BEAM IS  5.300E-01
CNSQ =  5.000E-15    V  =  2.000E+00
```


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WAVELENGTH	MOLECULAR SCATTER	MOLECULAR ABSORPTION	AEROSOL ATTENUATION	TOTAL ATTENUATION	TOTAL TRANSMITTANCE
1.060	.782E-03	.100E-02	.131	.13250	.34646
.550	.125E-01	.100E-02	.258	.27134	.11410
.530	.125E-01	.100E-02	.258	.27134	.11410

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```
WAVELENGTH DIAMETER    DIVERGENCE     POWER        PD           PRT
 1.060E+00  1.000E-02  3.000E-03  1.100E+07  6.000E-09  3.333E-02
CNSQ =  1.000E-14     V =  2.000E+00

THREE-PARAMETER TRUNCATED LOG-NORMAL DISTRIBUTION IS ASSUMED.
MEAN IRRADIANCE ON AXIS IS  1.976E-04 (W/M**2)
MEDIAN IRRADIANCE ON AXIS IS  8.429E-05 (W/M**2)
ONE HALF OF ALL PULSES WILL BE ABOVE  2.021E-04 OR BELOW  3.515E-05

WANDER IS NOT SIGNIFICANT.

MAGNITUDE OF WANDER IS SMALL COMPARED TO VACUUM BEAM DIVERGENCE.

BOTH WANDER AND SCINTILLATION VARY RANDOMLY PULSE-TO-PULSE.

OUTPUT CORRESPONDING TO THE MEAN IRRADIANCE IS  9.011E-07
```


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```
WAVELENGTH DIAMETER   DIVERGENCE    POWER       PD          PRT
 5.300E-01  1.000E-02  2.400E-03  7.000E+06  4.000E-09  3.333E-02
CNSQ =  1.000E-14     V =  2.000E+00

LOG-NORMAL DISTRIBUTION ASSUMED.
MEAN IRRADIANCE ON AXIS IS 2.130E-05 (W/M**2)
MEDIAN IRRADIANCE ON AXIS IS 9.471E-06 (W/M**2)
ONE HALF OF ALL PULSES WILL BE ABOVE  2.223E-05 OR BELOW  4.036E-05 (W/M**2)

BEAM WANDER IS NOT SIGNIFICANT.

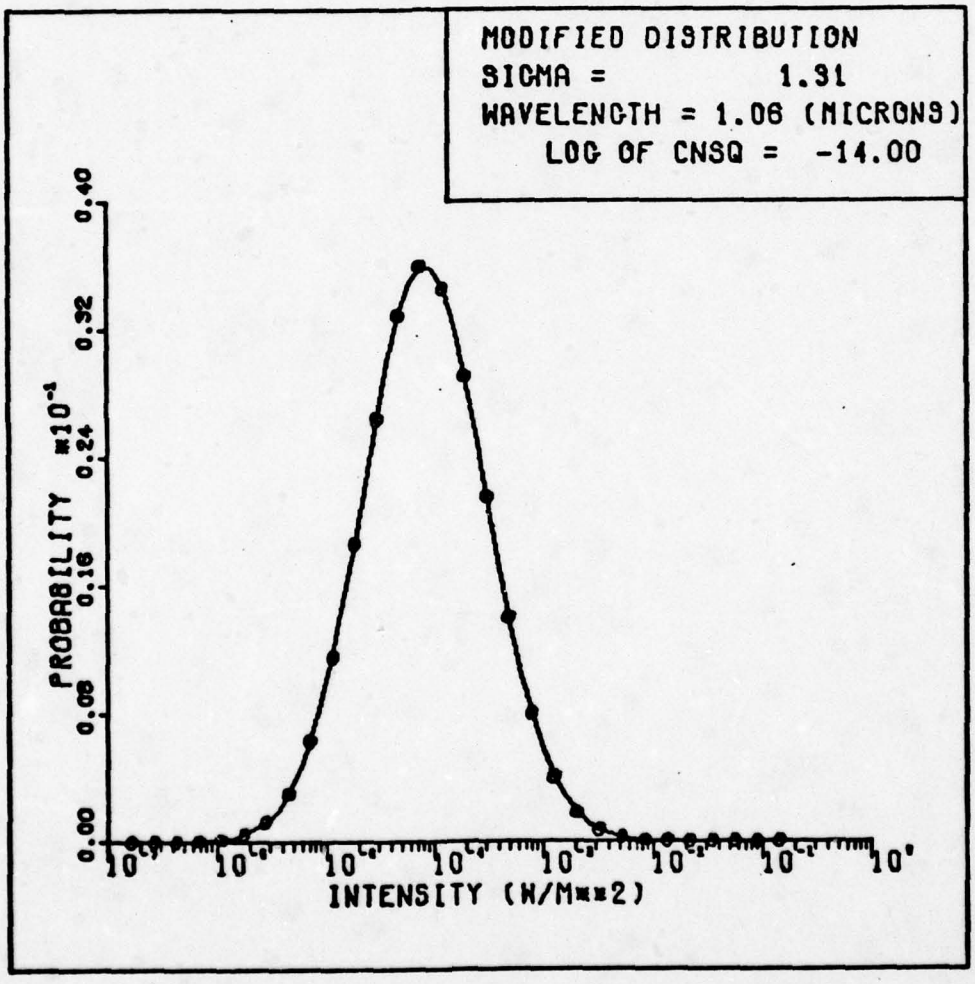
MAGNITUDE OF WANDER IS SMALL COMPARED TO VACUUM BEAM DIVERGENCE.

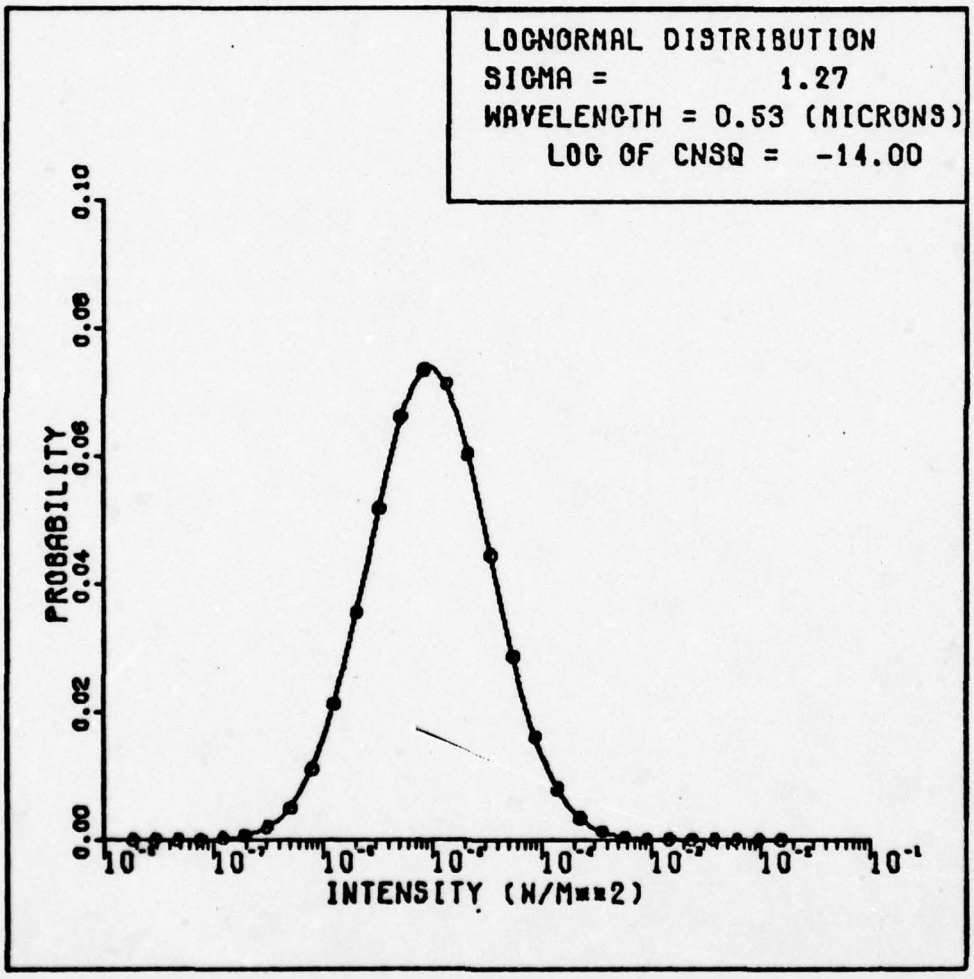
BOTH WANDER AND SCINTILLATION VARY RANDOMLY PULSE-TO-PULSE.

OUTPUT CORRESPONDING TO THE MEAN IRRADIANCE IS  9.714E-08

**********          ORORIOR   //// END  OF LIST ////
```


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MODIFIED DISTRIBUTION
SIGMA = 1.31
WAVELENGTH = 1.06 (MICRONS)
LOG OF CNSQ = -14.00
PROBABILITY *10^-1
0.00
0.08
0.16
0.24
0.32
0.40
10^-9
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
10^0
INTENSITY (W/M**2)


LOGNORMAL DISTRIBUTION
SIGMA = 1.27
WAVELENGTH = 0.53 (MICRONS)
LOG OF CNSQ = -14.00
PROBABILITY
0.00
0.02
0.04
0.06
0.08
0.10
INTENSITY (W/M**2)

```
WAVELENGTH DIAMETER   DIVERGENCE    POWER       PD          PRT
 1.060E+00  1.000E-02  3.000E-03  1.100E+07  6.090E-09  3.333E-02
CNSQ =  1.000E-16    V =  2.000E+00

LOG-NORMAL DISTRIBUTION ASSUMED.
MEAN IRRADIANCE ON AXIS IS 1.976E-04 (W/M**2)
MEDIAN IRRADIANCE ON AXIS IS 1.932E-04 (W/M**2)
ONE HALF OF ALL PULSES WILL BE ABOVE  2.228E-04 OR BELOW  1.676E-04 (W/M**2)

BEAM WANDER IS NOT SIGNIFICANT.

MAGNITUDE OF WANDER IS SMALL COMPARED TO VACUUM BEAM DIVERGENCE.

WANDER VARIES RANDOMLY PULSE-TO-PULSE. SCINTILLATIONS VARY SLOWLY.

OUTPUT CORRESPONDING TO THE MEAN IRRADIANCE IS  9.012E-07
```

```
WAVELENGTH DIAMETER   DIVERGENCE    POWER       PD          PRT
 5.300E-01  1.000E-02  2.400E-03  7.000E+06  4.000E-09  8.333E-02
CNSQ =  1.000E-16    V =  2.000E+00

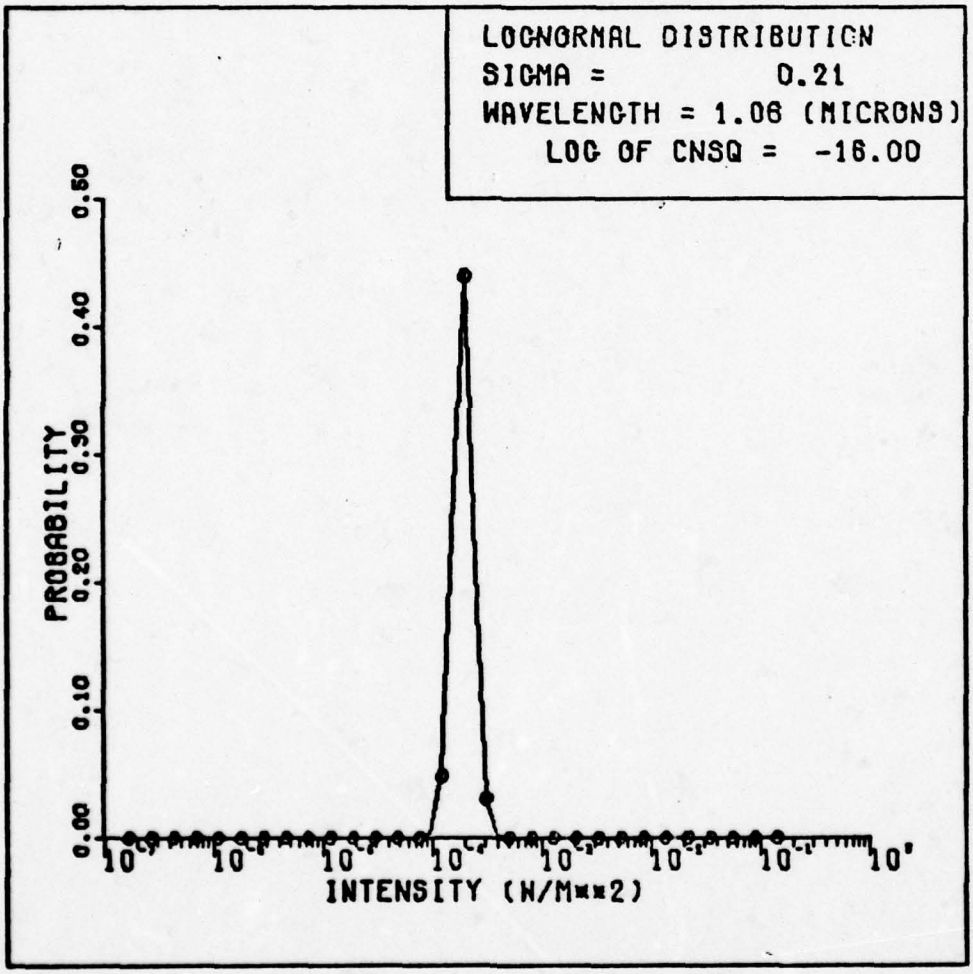
LOG-NORMAL DISTRIBUTION ASSUMED.
MEAN IRRADIANCE ON AXIS IS 2.131E-05 (W/M**2)
MEDIAN IRRADIANCE ON AXIS IS 1.950E-05 (W/M**2)
ONE HALF OF ALL PULSES WILL BE ABOVE  2.586E-05 OR BELOW  1.471E-05 (W/M**2)

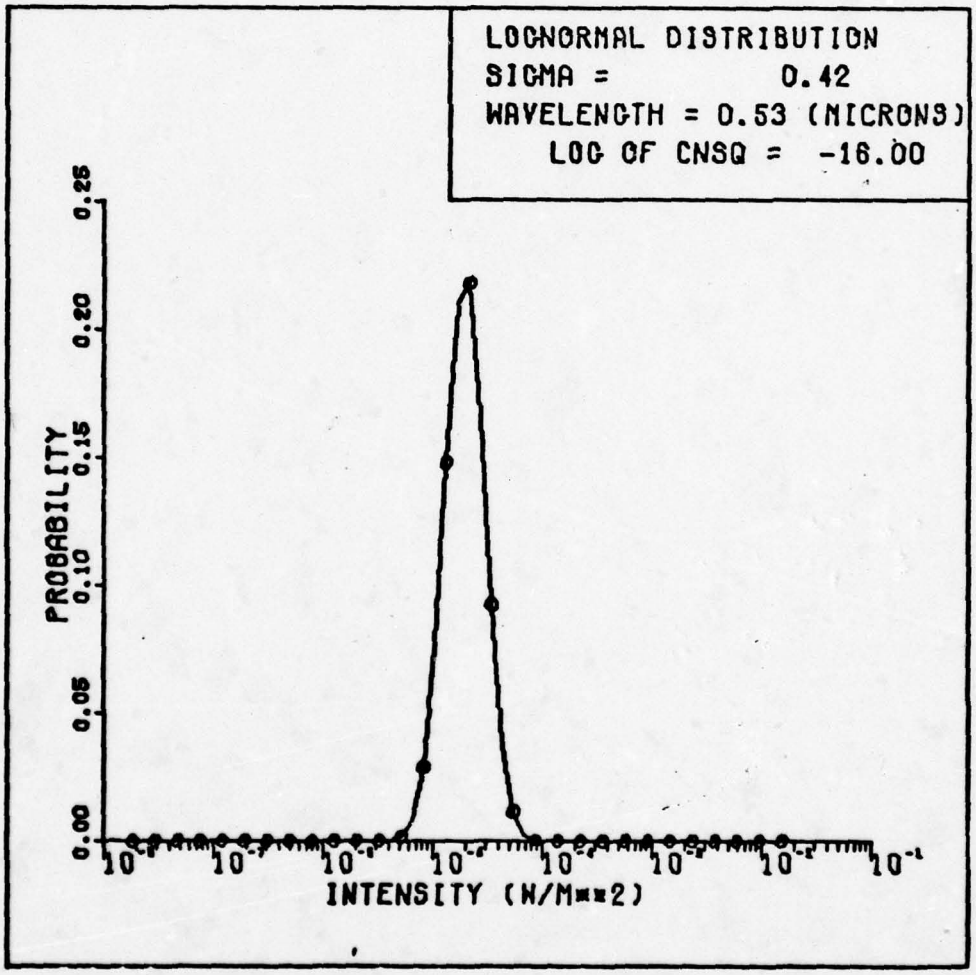
BEAM WANDER IS NOT SIGNIFICANT.

MAGNITUDE OF WANDER IS SMALL COMPARED TO VACUUM BEAM DIVERGENCE.

BOTH WANDER AND SCINTILLATION VARY RANDOMLY PULSE-TO-PULSE.

OUTPUT CORRESPONDING TO THE MEAN IRRADIANCE IS  9.718E-08
```


LOGNORMAL DISTRIBUTION
SIGMA = 0.21
WAVELENGTH = 1.06 (MICRONS)
LOG OF CNSQ = -16.00
PROBABILITY
0.00
0.10
0.20
0.30
0.40
0.50
INTENSITY (W/M**2)


LOGNORMAL DISTRIBUTION
SIGMA = 0.42
WAVELENGTH = 0.53 (MICRONS)
LOG OF CNSQ = -16.00
PROBABILITY
0.00
0.05
0.10
0.15
0.20
0.25
INTENSITY (W/M**2)

Appendix C

Molecular Absorption Computer Codes

The Air Force Geophysical Laboratory has been studying molecular absorption in the atmosphere for many years. The basic approach has been to determine individual absorption lines for each molecule and each set of energy levels. This has been accomplished both by theoretical calculations and by laboratory measurements. Although only the seven major constituents of the atmosphere (in terms of absorption) have been considered, over 150,000 individual absorption lines have been tabulated (Ref 21). This data base is constantly updated as new or improved information becomes available. It is contemplated to either add to this compilation, or compile separately, a similar collection for the major pollutants, notably hydrocarbons (Ref 8). This would be of particular interest in the visible and near-IR, since in most of this range little absorption is present due to the primary constituents.

The compilation is on magnetic tape and consists, in addition to identification by molecule, isotope and quantum levels of the transition involved, the following information:

ν = frequency (wavenumber) in cm^{-1}
S = line intensity in cm^{-1}/molecule cm^{-2} at 296°K
α = half-width in cm^{-1}atm at 296°K
E^{11} = energy of the lower state in cm^{-1}

A great deal of effort has gone into understanding the line-shape of these transitions and into modeling the effects of temperature and pressure on the lineshapes.

The data base and detailed knowledge of the lineshapes have led to the development of four different types of computer codes to extract useful information from the data. An example of each is described below.

Program LIN

Program LIN is the basic brute force approach to obtaining high resolution absorption spectra. It requires that the number densities of the seven absorbing species be input at up to 15 pressure levels of interest, as well as the pressure and temperature at each level. Then the limits of the frequency range to be considered, V1 and V2, and the interval at which results are printed (or more commonly, plotted), DELV, are entered. Additional parameters needed are DV, the interval at which monochromatic calculations are made; BOUND, the frequency range from the frequency of calculation to which the program searches for lines and A, the half-width of a triangular slit function which is convolved with the monochromatic results. Another parameter, DEPTH, can be used to reject lines which have an optical depth (line strength x molecular number density) below a certain level. The general slant path case also requires a path description, generally a range and the secant of the zenith angle.

A general flow chart of the program is given in Figs. C-1 and C-2. No details of the calculations are given, and large parts of the program are not included at all. Those omitted are essentially bookkeeping sections which are very necessary for the proper operation of the program. At the initial stage of reading in the line parameters, if the frequency range from V1-A-BOUND to V2 + A + BOUND contains over 3000 lines, the calculation cannot proceed directly, but must be broken up into segments. The calculations of transmittance are completed for one segment, up to a frequency VV, which is (A+BOUND) below the upper line included. Then, all lines above VV-(A+BOUND) must be retained while new lines are read in so that information in the boundary areas is not lost. If A and BOUND are not carefully chosen, this can lead to adding only a few lines each time or even failure of the whole approach. This is especially true in spectral regions with many lines. This effect can be minimized to some extent by using higher values of DEPTH, thus rejecting more lines. In dense regions this is not satisfactory either, since the cumulative effort of several weak lines may be significant.

The discussion above gives a very sketchy idea of the line-by-line approach and a small feeling for the amount of calculation involved. Computer processing time can easily run into the hundreds of seconds for spectral regions of reasonable size.

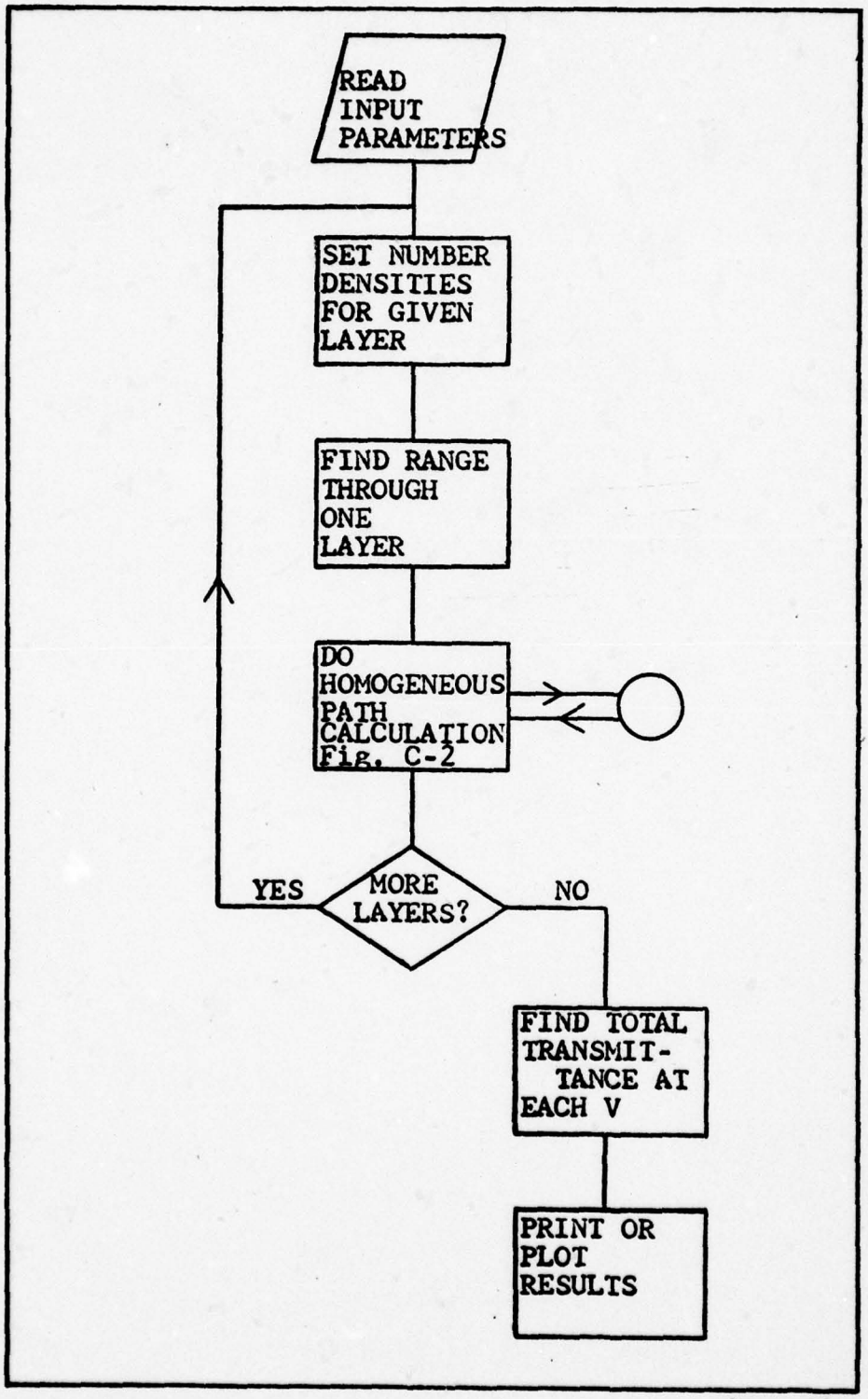
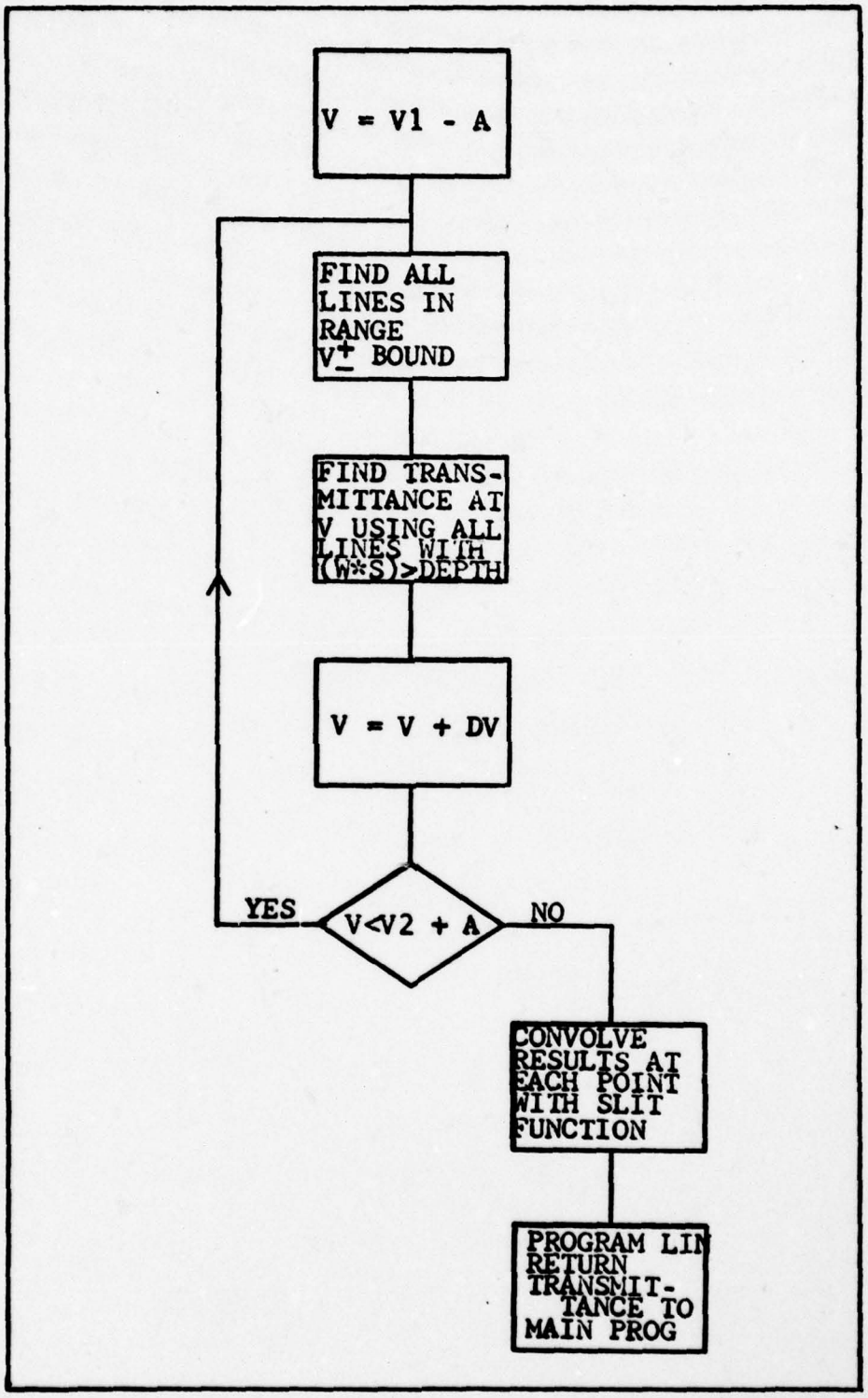


Fig. C-1. Overall Flow of Program LIN



(Ref 8)

Fig. C-2. Homogeneous Path Calculation (Program LIN)

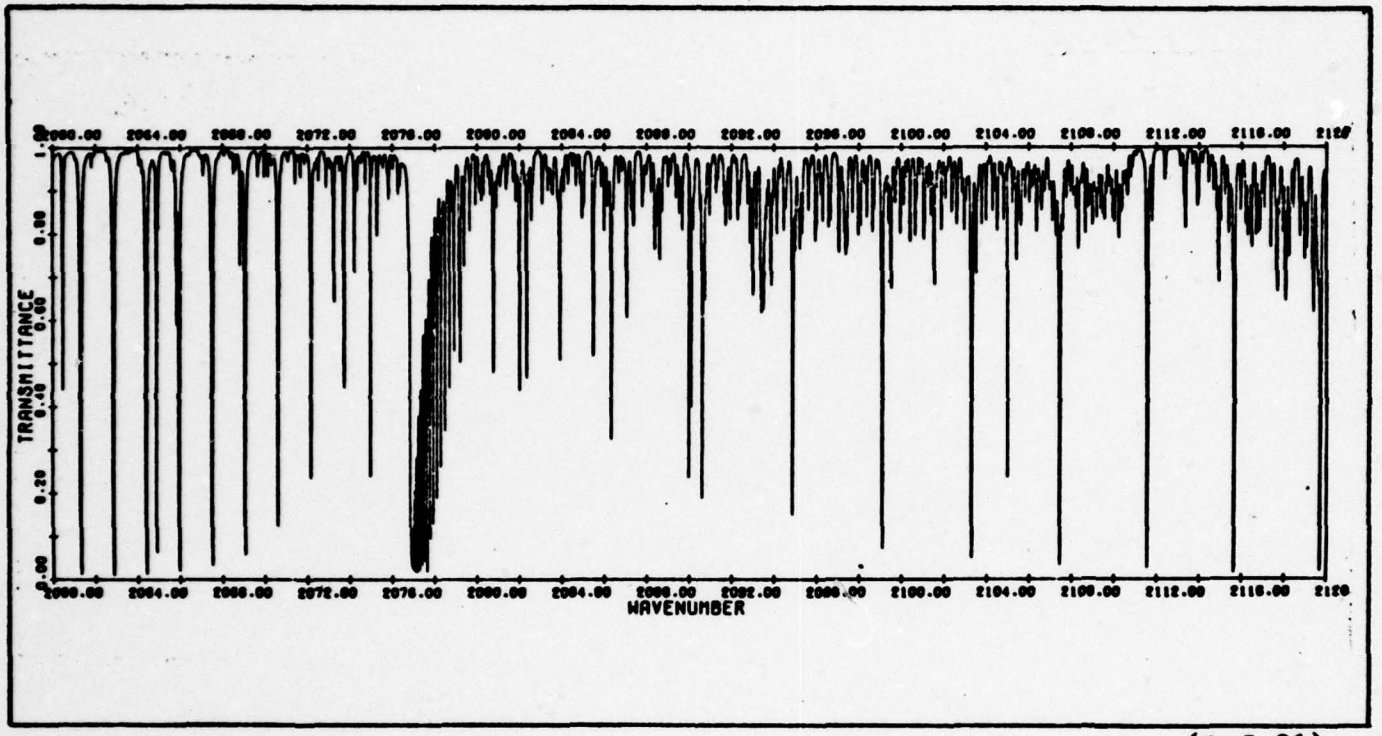
An example of the output from LIN is given in Fig. C-3. It is, of course, also possible to get a numerical listing of the output.

There are versions of this program which will accept convolution functions other than the triangular slit function. This would be useful for a particular laser line-shape or for a receiver spectral response, where very accurate results are required.

Program LASER

Program LASER (Ref 24) is designed to give strictly monochromatic results. The calculation of the transmittance is exactly the same as that for a single frequency in Program LIN. The calculation is repeated for six different standard atmosphere models, hence giving a feel for the range of absorption coefficient values to be expected under various conditions. A sample of the output is given in Fig. C-4. (This is from an older version of the program, which included only five standard models. It was selected to show the 1.06 micron results.)

Note that the output gives values for the Rayleigh scattering coefficient, as well as aerosol attenuation coefficients for two common aerosol models. These will not be discussed here, but it is clear that this form of output is excellent for giving an estimate of the relative importance of various effects.



(Ref 21)

Fig. C-3. Line-by-Line Transmittance Results

λ=1.06μm															
	TROPICAL		MIDLATITUDE SUMMER		MIDLATITUDE WINTER		SUBARCTIC SUMMER		SUBARCTIC WINTER		AEROSOL CLEAR		AEROSOL HAZY	
Ht(km)	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_m (km^{-1})	σ_m (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})	k_a (km^{-1})	σ_a (km^{-1})
0	<E-06	8.04E-04	<E-06	8.20E-04	<E-06	8.91E-04	<E-06	8.38E-04	<E-06	9.39E-04	1.98E-02	6.79E-02	9.63E-02	3.31E-01
0-1		7.6?E-04		7.81E-04		8.43E-04		7.98E-04		8.77E-04	1.31E-02	4.50E-02	5.82E-02	2.00E-01
1-2		6.99E-04		7.06E-04		7.52E-04		7.21E-04		7.70E-04	5.71E-03	1.96E-02	2.13E-02	7.31E-02
2-3		6.33E-04		6.38E-04		6.70E-04		6.50E-04		6.82E-04	2.43E-03	8.36E-03	7.78E-03	2.67E-02
3-4		5.72E-04		5.77E-04		5.99E-04		5.84E-04		6.06E-04	1.15E-03	3.94E-03	2.84E-03	9.76E-03
4-5		5.19E-04		5.21E-04		5.37E-04		5.24E-04		5.40E-04	7.23E-04	2.49E-03	1.04E-03	3.56E-03
5-6		4.69E-04		4.69E-04		4.80E-04		4.71E-04		4.82E-04	5.27E-04	1.81E-03	5.27E-04	1.81E-03
6-7		4.22E-04		4.21E-04		4.27E-04		4.23E-04		4.29E-04	4.27E-04	1.47E-03	4.27E-04	1.47E-03
7-8		3.80E-04		3.78E-04		3.80E-04		3.79E-04		3.81E-04	4.18E-04	1.44E-03	4.18E-04	1.44E-03
8-9		3.41E-04		3.38E-04		3.36E-04		3.38E-04		3.34E-04	4.15E-04	1.43E-03	4.15E-04	1.43E-03
9-10		3.04E-04		3.02E-04		2.97E-04		3.01E-04		2.88E-04	4.01E-04	1.38E-03	4.01E-04	1.38E-03
10-11		2.72E-04		2.69E-04		2.59E-04		2.64E-04		2.46E-04	3.84E-04	1.32E-03	3.84E-04	1.32E-03
11-12		2.41E-04		2.39E-04		2.22E-04		2.26E-04		2.10E-04	3.81E-04	1.31E-03	3.81E-04	1.31E-03
12-13		2.13E-04		2.11E-04		1.90E-04		1.95E-04		1.80E-04	3.75E-04	1.29E-03	3.75E-04	1.29E-03
13-14		1.88E-04		1.83E-04		1.63E-04		1.67E-04		1.54E-04	3.56E-04	1.22E-03	3.56E-04	1.22E-03
14-15		1.66E-04		1.56E-04		1.40E-04		1.44E-04		1.31E-05	3.42E-04	1.18E-03	3.42E-04	1.18E-03
15-16		1.44E-04		1.33E-04		1.20E-04		1.23E-04		1.12E-05	3.23E-04	1.11E-03	3.23E-04	1.11E-03
16-17		1.24E-04		1.14E-04		1.03E-04		1.06E-04		9.63E-05	3.13E-04	1.08E-03	3.13E-04	1.08E-03
17-18		1.05E-04		9.72E-05		8.80E-05		9.14E-05		8.25E-05	3.06E-04	1.05E-03	3.06E-04	1.05E-03
18-19		8.63E-05		8.29E-05		7.53E-05		7.86E-05		7.06E-05	2.77E-04	9.51E-04	2.77E-04	9.51E-04
19-20		7.16E-05		7.07E-05		6.45E-05		6.75E-05		6.05E-05	2.18E-04	7.48E-04	2.18E-04	7.48E-04
20-21		5.96E-05		6.02E-05		5.51E-05		5.80E-05		5.17E-05	1.59E-04	5.45E-04	1.59E-04	5.45E-04
21-22		4.98E-05		5.14E-05		4.70E-05		4.99E-05		4.42E-05	1.17E-04	4.03E-04	1.17E-04	4.03E-04
22-23		4.19E-05		4.38E-05		4.01E-05		4.29E-05		3.78E-05	8.89E-04	3.06E-04	8.89E-04	3.06E-04
23-24		3.55E-05		3.74E-05		3.43E-05		3.69E-05		3.23E-05	6.93E-05	2.38E-04	6.93E-05	2.38E-04
24-25		3.02E-05		3.19E-05		2.93E-05		3.15E-05		2.76E-05	5.66E-05	1.94E-04	5.66E-05	1.94E-04
25-30		2.01E-05		2.15E-05		1.95E-05		2.13E-05		1.84E-05	2.85E-05	9.79E-05	2.85E-05	9.79E-05
30-35		9.20E-06		9.89E-06		8.79E-06		9.98E-06		8.14E-06	8.02E-06	2.76E-05	8.02E-06	2.76E-05
35-40		4.37E-06		4.71E-06		3.95E-06		4.73E-06		3.66E-06	2.11E-06	7.26E-06	2.11E-06	7.26E-06
40-45		2.15E-06		2.31E-06		1.83E-06		2.33E-06		1.68E-06	<E-06	1.91E-06	<E-06	1.91E-06
45-50		1.09E-06		1.19E-06		<E-06		1.21E-06		<E-06		<E-06		<E-06
50-70		<E-06		<E-06				<E-06						
70-100														

(Ref 24)

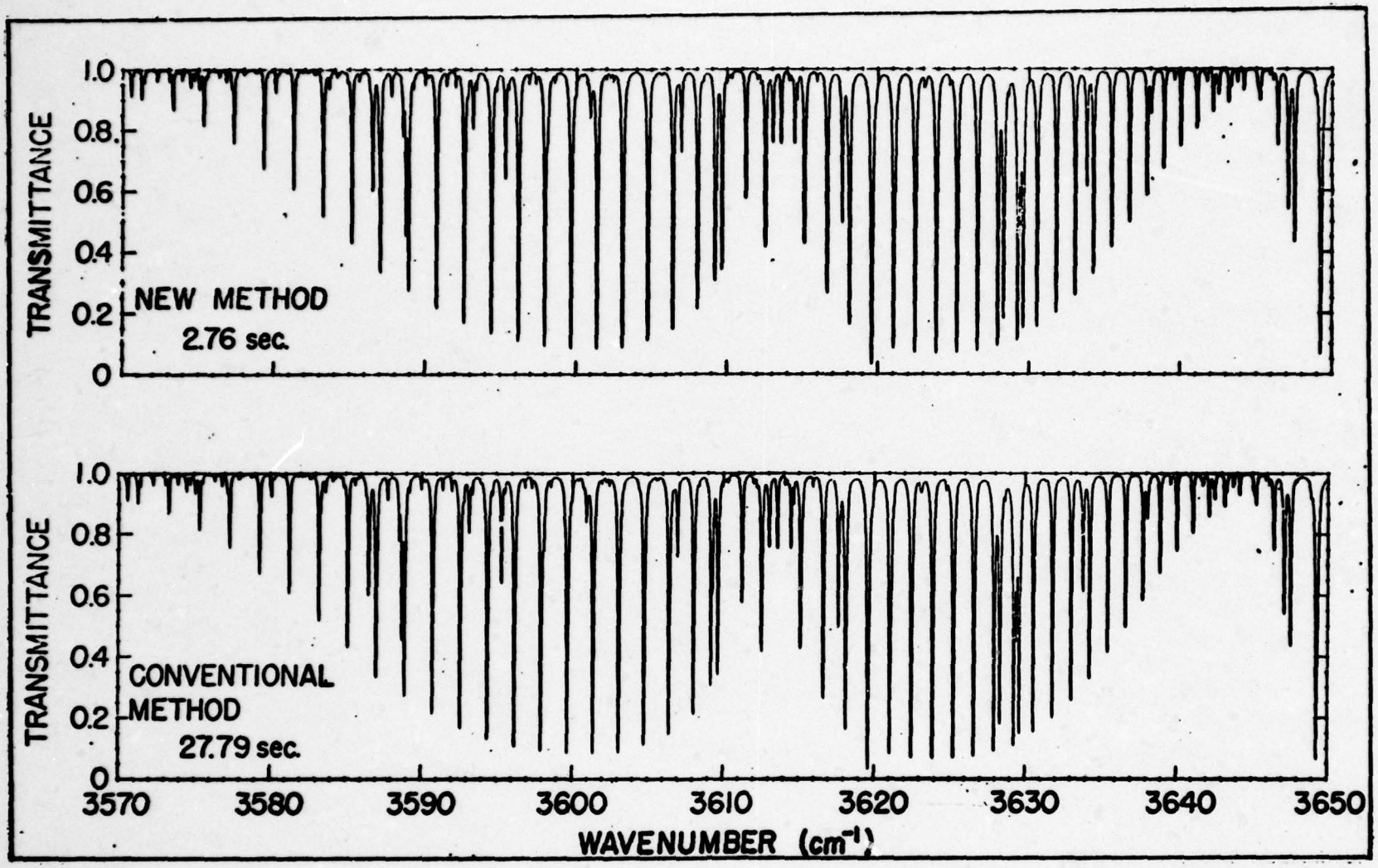
Fig. C-4. Results of Program LASER

Since there is no information available for other frequencies, the choice of V, A, BOUND and DEPTH are critically important in this case. The problem mentioned in Chapter III concerning precisely defined frequencies (or wavelengths), and carefully picking A to describe the line-width of the laser beam could make a difference of orders of magnitude in the absorption, particularly for very narrow laser lines.

Program HIRACC

Program HIRACC (High Resolution Absorption Coefficient Code) is a program developed at AFGL (Ref 7) to replace the line-by-line calculation. The version described is the basic version for the uniform path case, using a Lorentzian line shape, suitable for low altitude use. A program basically the same, called HIRACV, which uses an approximation to the Voight lineshape and is valid at all altitudes, is being incorporated into a much more general code called (at least at present) FASCODE, for Fast Atmospheric Signature Code (Ref 8). This code will give a capability to calculate not only absorption, but also atmospheric emission, for the general slant path case, either looking up or down through the atmosphere. This will give an essentially complete characterization of an atmospheric path, for molecular effects.

Fig. C-5 is taken from a preliminary report on program HIRACC, and compares the results to those of a conventional line-by-line calculation. Note particularly the saving in



(Ref 7)

Fig. C-5. Comparison of Output From HIRACC (New) and LIN (Conventional)

calculation time. The savings in time have been made primarily by approximating the Lorentz line shape by the sum of three functions. The Lorentzian falls to zero very slowly in the far wings, and this makes use of uniform intervals in the computer calculation very uneconomical of time. The three functions into which the Lorentz shape is decomposed behave as fast, slow and very slow functions of frequency, and are sampled at different intervals. This results in about a factor of five improvement in calculating time, when the appropriate sampling intervals are chosen. Another factor of two comes from using tabulated values for the three functions, rather than calculated, and from more optimized selection of calculational steps in loops which are used many times.

A major difference between the approaches of this program and program LIN is that HIRACC calculates all the absorption coefficients due to one line, then moves to the next line, etc.. Program LIN, on the other hand, calculates the contributions from all lines at a given frequency, then indexes in frequency and repeats. This requires the HIRACC program to sum the absorption at each frequency to obtain the output, but it reduces the number of references to the line data. BOUND, in the case of HIRAAC is automatically set to 48 times the half-width of the line (other multiples are possible, if the decomposed functions are changed). Lines are not rejected by a DEPTH parameter, and calculations of absorption coefficient are made between V1 and V2, at

intervals of DV, with no slit function convolution. As in LIN, computations are broken into segments (called Panels) when necessary.

Output from the basic program, as in the case of LIN, is a binary file containing a header record with all the input parameters, followed by Panel header information and then absorption coefficients for each frequency of the panel. This output is normally plotted, as in Fig. 4. This is a plot of transmittance over a 100 km range at sea level, using the number densities of the midlatitude winter model.

Appendix D

The Log-Normal Distribution

The description here is taken from a book by Aitchison (Ref 2) which primarily addresses the social sciences. Only a few of the mathematical properties of the distribution (or properly, the distributions) are considered here. The basic nature of the distributions is that the logarithm of the variable, or the logarithm of some simple function of the variable, is normally distributed.

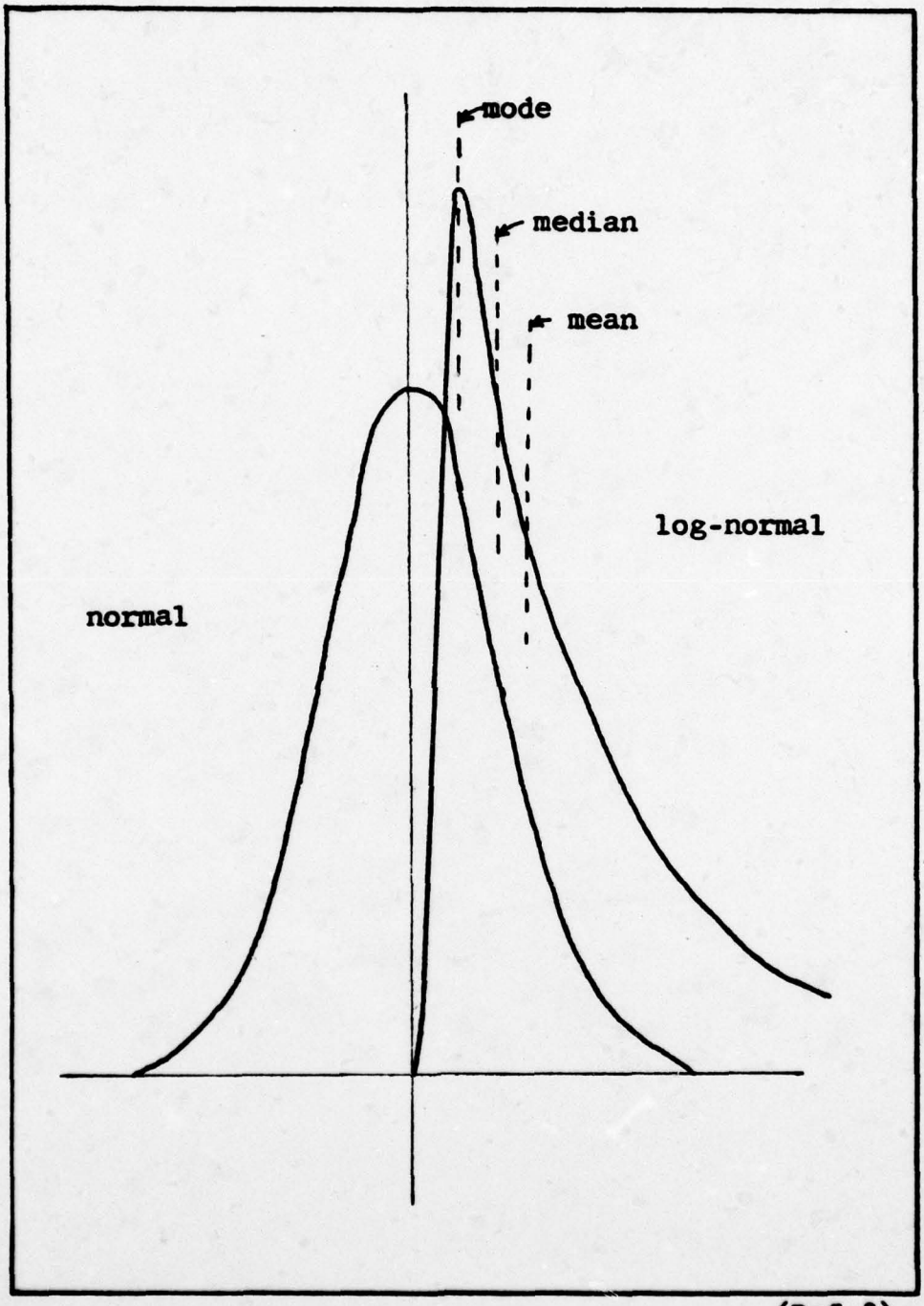
Two-Parameter Log-Normal Distribution

The simplest such distribution is the two-parameter case. Here, the two parameters are μ, the mean of the log of the variable and σ^2, the variance in the log. In this case, the probability density can be expressed as

$$\frac{dP}{dx} = \frac{1}{x\sigma(2\pi)^{\frac{1}{2}}} \exp\left[-\frac{(\log x - \mu)^2}{2\sigma^2}\right] \qquad (1)$$

for $x > 0$.

Unlike the normal distribution, this is limited to positive values of x, and the mean, median and mode are all distinct. Fig. D-1 is from Aitchison, and shows a normal and a log-normal curve. The three central measures fall at the following values of x.



(Ref 2)

Fig. D-1. Log-Normal vs. Normal Distribution

$$\text{Mean} = \text{EXP}(\mu + \tfrac{1}{2}\sigma^2) \quad (2)$$

$$\text{Mode} = \text{EXP}(\mu - \sigma^2) \quad (3)$$

$$\text{Median} = \text{EXP}(\mu) \quad (4)$$

The quantile points of the distribution can most easily be found from those of the normal distribution, which are widely tabulated. If q is the quantile of the normal distribution and Q is the quantile of the log-normal, these are related by

$$Q = \text{EXP}(\mu + q\sigma) \quad (5)$$

Hence, the lower and upper quartile points of the log-normal are at $x = \text{EXP}(\mu - .67\sigma)$ and $x = \text{EXP}(\mu + .67\sigma)$, respectively. These are the values used in the program to describe the range in the printed output.

Three-Parameter Log-Normal Distribution

The three-parameter function is basically just the two-parameter distribution with the variable x displaced by an amount τ, so that $\log(x - \tau)$ is normally distributed. Since the two-parameter distribution is only defined for $x > 0$, the three-parameter distribution is only valid for $x > \tau$. The probability of $x \leq \tau$ is zero.

All of the central measures and the quantiles are just displaced by an amount τ, so that

$$\text{Mean} = \tau + \text{EXP}(\mu + \tfrac{1}{2}\sigma^2) \quad (6)$$

$$\text{Mode} = \tau + \text{EXP}(\mu - \sigma^2) \quad (7)$$

$$\text{Median} = \tau + \text{EXP}(\mu) \tag{8}$$

$$Q = \tau + \text{EXP}(\mu + q\sigma) \tag{9}$$

The reason for using the three-parameter distribution (other than the experimental results of Ref 9) is that a small negative value of irradiance can be used for τ, thus permitting an irradiance of zero to be observed, which should be admitted as a possibility in strong turbulence. This assumption of a negative value for τ, necessarily means that a truncated distribution must be considered, since a negative irradiance is physically meaningless.

The truncated distribution is much more complicated to deal with, but if τ is chosen as a very small negative quantity, there should be little loss in accuracy in assuming the same form as above for the central measures and quantiles, except for quantiles which lie very near zero. This is because only the effect of the few points between τ and zero are being neglected.

Appendix E

Program Changes to Vary Beam Parameters

In order to more readily examine the results of changing beam parameters, the following changes can be made to Program Pulse. The cards below replace the same numbered cards in the program, or are inserted where indicated by numerical order.

```
      NCK = 0                                                    000721
 2    IF(NCK.EQ.0) GO TO 23                                      000880
      NCK = NCK + 1                                              000890
      DECODE (70,103,KRUD)WVLN(NCK),DIVERG(NCK),
        POWER(NCK),                                              000900
     C PD(NCK),PRT(NCK)                                          000910
      GO TO 21                                                   000912
23    PRINT(6,24)NUMBER                                          000914
24    FORMAT("0 MORE LINES WERE INPUT THAN YOU
        CALLED FOR."                                             000916
     C "ALL LINES PAST ",I2,"WERE IGNORED.")                     000920
```

If these changes are made, NUMBER must be input before BEAM cards. If NUMBER is input as 3 and less than 3 BEAM cards are input, the program will not run to completion, since no default values are included for beam 3. An additional DATA statement with beam 3 default parameters would allow this sort of input.

Vita

William Hugh MacInnis was born on 4 June 1941 in Buffalo, New York. He graduated from Kensington High School in Buffalo in 1959, subsequently attending Cornell University. There, he graduated with the degree of Bachelor of Engineering Physics, in 1964. Entering the U.S. Air Force shortly after graduation, he entered navigator training and graduated in March 1966, followed by Electronic Warfare school. He then served as a B-52 Electronic Warfare Officer, until 1970, when he served a brief tour as a C-130 navigator. This was followed by five years of duty as a crewmember in Special Operations (Combat Talon) C-130's, both in Southeast Asia and West Germany. He entered the School of Engineering, Air Force Institute of Technology, in June 1976.

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A model is described which calculates the irradiance probability distrbution at the receiver of a system consisting of a co-located laser transmitter and receiver, with the beam being reflected from a small,highly reflective target. The beams considered have short (10 nsec) pulses at low repetition rates (30 Hz). Atmospheric effects included are molecular scattering and absorption,aerosol extinction and turbulence. It is found that, in normal daytime weather conditions, it is common to have pulse-to-pulse irradiance variations at the receiver of two orders of magnitude.

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